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NUMERICAL MODELLING OF BIRCH POLLEN EMISSIONS AND DISPERSION ON REGIONAL AND CONTINENTAL SCALES

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Title
Numerical modelling of birch pollen emissions and dispersion on regional and continental scales

Abstract
Birch pollen is one of the most prevalent allergens in Northern Europe. Nearly every spring, birch pollen is found in Finland before the start of local flowering. Sometimes, its concentrations are so high that they cause symptoms in allergic persons. Such episodes are caused by long-range transport of pollen grains from other regions, in which the flowering started earlier. Prediction of these episodes requires European-scale modelling of pollen distribution.

The goal of this study was to develop a European-wide, bio-physical, numerical prediction system for birch flowering, pollen release, and dispersion in the atmosphere.

The pollen forecasting system is based on both the atmospheric dispersion modelling system SILAM developed at FMI and numerical weather prediction models. In order to predict birch pollen concentrations, several input datasets and modules for pollen emissions were developed: a European birch habitat map, phenological model parameters for the start of birch flowering in Europe, and a pollen release model. The study also included an evaluation of the features of the input datasets, such as phenological observations in Europe, and the reliability of the new pollen forecasting system.

The SILAM pollen forecasting system allows for detailed predictions of pollen distribution in space and time, and enables the simulation of long-range pollen transport episodes, which cannot be predicted from in-situ observations. Moreover, this pollen dispersion model can be helpful in many research applications, such as gene flow studies or in assessing pollen concentrations under future climate conditions.

The second goal of this study was to delineate the source areas of long-range transported birch pollen observed in North-Eastern Europe. In general, long-range transported pollen reaches Finland some days, although sometimes even weeks, before birch trees pollinate in Finland. Typically, the long-range transported pollen originates from the south, mainly from the Baltic countries; however, very high pollen counts are observed when pollen grains come from the southeast, from the vast Russian birch stands. In some cases, a smaller proportion of pollen can travel from Sweden, Poland, or even Germany.

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Nimeke

Koivun siitepölyn päästön ja leviämisen ennustaminen ilmakehämalleilla Euroopassa

Tiivistelmä

Koivu on tärkein siitepölyallergian aiheuttaja Pohjois-Euroopassa. Lähes joka kevät Suomessa havaitaan koivun siitepölyä jo ennen paikallisen kukinnan alkua. Toisinaan määrät ovat niin suuria, että ne aiheuttavat oireita allergisille. Tässä väitöskirjatyössä on selvitetty, mistä siitepölyä Suomeen kulkeutuu ja kehitetty ilmakehämalleihin perustuva ennustussysteemi koivun siitepölyn päästölle, kulkeumalle ja pitoisuuksille Euroopassa.

Ilmakehämalleihin perustuvat siitepölyennusteet mahdollistavat sekä ajallisesti että paikallisesti tarkemmat siitepölyennusteet sekä siitepölyn kaukokulkeumaepisodien ennustamisen, joka ennen mallin kehittämistä oli lähes mahdotonta. Myös monissa tutkimussovellutuksissa, esimerkiksi geenivirtatutkimuksissa tai arvioitaessa siitepölypitoisuuksia menneisyyden tai tulevaisuuden ilmastossa, siitepölyn leviämistä kuvaava malli voi olla avuksi.

Yleensä siitepölyä kulkeutuu Suomeen muutamia päiviä, toisinaan jopa viikkoja ennen kuin koivut kukkivat Suomessa. Tyypillisesti tällainen kaukokulkeutunut siitepöly on lähtöisin etelästä Baltiasta, mutta todella korkeat pitoisuudet tulevat Venäjän laajoista koivikoista kaakosta. Joissakin harvemmissa tapauksissa siitepölyä voi kulkeutua Ruotsista, Puolasta tai jopa Saksasta saakka.

Siitepölypitoisuuksien ennustesysteemi perustuu aineen leviämistä ilmakehässä kuvaavaan SILAM-malliin, joka on kehitetty Ilmatieteen laitoksella. Säätiedot siitepölyn päästön ja leviämisen laskemista varten malli saa säänennustusmallista. Tässä väitöskirjatyössä on kehitetty siitepölypitoisuuksien arvioimista varten erityisesti siitepölypäästön kannalta tärkeitä tekijöitä kuten koivukartta ja koivun kukinnan alkua kuvaava malli koko Euroopan alueelle. Lisäksi on kuvattu siitepölyn vapautuminen norkoista. Myös tämän biologis-fysikaalisen siitepölyn ennustussysteemin tulosten luotettavuutta on arvioitu samoin kuin fenologisten havaintojen edustavuutta Euroopassa.

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To my dear (and irritating) kids:

Kaisla,
Oula,
Sameli,
and
Hilla

PREFACE

This thesis has taken a long time — too long for a doctoral dissertation, but who can guess all that you can find along the path, what kind of hills you will climb over, and what kind of treetops you will reach out to.

The year was 2003 when it all started. The aerobiology unit at the University of Turku had had a problem for several years. During several springs, they found pollen well before their local flowering, but they were not able to say where it came from, or at least they did not know how to predict it. Thus, Auli Rantio-Lehtimäki asked FMI for help. Maybe we could help them.

Surely we knew how to help. Or, at least we wanted to help, especially after Auli offered us some money. At that time, I was looking for a topic for my dissertation, but I had not found the right one. When I was asked if I was interested in it, I knew immediately that this would be *it*. I could hardly have had better luck.

Young, eager, and promising Mikhail Sofiev from FMI promised to supervise me. Also, in this respect, I could hardly have been luckier. In addition, Prof. Jaakko Kukkonen from FMI agreed to supervise me and brought his experience. Full of enthusiasm and faith in the future, we threw ourselves into the work, completely ignorant of the problem. Prof. Hannu Savijärvi from the University of Helsinki has patiently accepted all of my study plans during this seemingly never-ending project, despite the subject being far from his own expertise. Thank you!

I must confess that, at first, I was unsure whether this was ever a doctoral dissertation, but the problem was excitingly interesting. If this topic hit a rock, there would be always something else.

Rocks indeed appeared. The outcome is quite different from what we had thought during our first gusts of enthusiasm. My identity as a meteorologist has been tested. At the beginning, we thought that we would just take all of the biological information from the literature and put it into the SILAM model. However, only little was available. With all the vigour of an atmospheric scientist, I did a belly landing into the secrets of biology and forest research. It has been very rewarding.

I have travelled a long path and tripped over many rocks. Fortunately, I have not had to walk this path alone. I could have not gone alone, because so many things have come across along the way that nobody would have been able to survive on his or her own. But, of course, this is not the end of the path. The path has already been branched — people have found new tracks, and new wanderers have joined the track. Very special thanks to Hanna Ranta and Tapio Linkosalo, who were always ready to help me and had advised and answered all my questions. Siegfried Jäger, Elena Severova, and many other aerobiologists, phenologists, and other scientists in different parts of Europe have travelled with me on this trip. They have provided data, knowledge, and their own interest, which inspired to continue. This would have been nothing without your help.

I am also grateful to my employer Finnish Meteorological Institute, which has provided the perfect working environment to make this work, as well as to the Meteorological Research Unit and its past and present heads, Prof. Mikko Alestalo, Juhani Damski, and in particular, Prof. Sylvain Joffre, who gave valuable comments on the manuscript. I also want to acknowledge all my wonderful colleagues at FMI and the NWP group, which have been piloted by Laura Rontu, Carl Fortelius, and Sami Niemelä throughout my career. Once again, I have been very lucky to get the best bosses that anyone could imagine.

Also, my family has been important. My mum and dad, Maija-Leena and Tapio Seppälä, have allowed me to grow in the healthy spirit of curiosity. My children Kaisla, Oula, Sameli, and Hilla have offered moments of happiness that even the most interesting research cannot provide, and my husband Niilo has successfully taken care of our children, so that both of us could have the same possibilities to do research.

Helsinki, September 2013,
Pilvi Siljamo

ABBREVIATIONS AND TERMINOLOGY

Comb, combination	Combination of phenological and pollen observations, used in phenological temperature sum maps
DD	Degree day, the unit of the temperature sum; $DD = \Sigma(T_{daily\ ave} - T_{threshold})$ if $T_{daily\ ave} > T_{threshold}$
EAN	European Aeroallergen Network
ECMWF	European Centre for Medium Range Weather Forecasts, or its global numerical weather prediction model
ERA-40	ECMWF's 40-year re-analysis covering the period from mid-1957 to mid-2002
F	False alarm rate, or the probability of false detection; F = (number of false alarms) / (number of observations)
FAR	False alarm ratio; FAR = (number of false alarms) / (total forecasted occurrences)
FMI	Finnish Meteorological Institute
GMO	Genetically modified organism
HIRLAM	High Resolution Limited Area Model, the regional numerical weather prediction model used operationally at FMI
HYSPLIT	Hybrid Single Particle Lagrangian Integrated Trajectory Model, an atmospheric trajectory model
HR	Hit rate; HR = (number of hits) / (observed number of "yes" cases)
KSS	Hanssen and Kuipper's skill score, true skill statistics; KSS = HR - F
LRT	Long-range transport. Synoptic scale transport of airborne components over distances of up to thousands of kilometres
LU	Leaf unfolding; also used in phenological temperature sum maps
NWP	Numerical weather prediction
Regional transport	Meso-scale transport over distances of up to hundreds of kilometres
SILAM	System for Integrated Modelling of Atmospheric Composition, the operational atmospheric dispersion model developed and used at FMI

CONTENTS

LIST OF ORIGINAL PUBLICATIONS

I
Siljamo P, Sofiev M, Ranta H, Linkosalo T, Kubin E, Ahas R, Genikhovich E, Jatczak K, Jato V, Nekovar J, Minin A, Severova E, Shalaboda V (2008) Representativeness of point-wise phenological *Betula* data collected in different parts of Europe. *Global Ecology and Biogeography*, **17**:489–503.

II
Sofiev M, **Siljamo P**, Ranta H, Linkosalo T, Jaeger S, Rasmussen A, Rantio-Lehtimäki A, Severova E, Kukkonen J (2013) A numerical model of birch pollen emission and dispersion in the atmosphere. Description of the emission module. *International Journal of Biometeorology*, **57**:45–58.

III
Siljamo P, Sofiev M, Filatova E, Grewling Ł, Jäger S, Khoreva E, Linkosalo T, Ortega Jimenez S, Ranta H, Rantio-Lehtimäki A, Svetlov A, Veriankaitė L, Yakovleva E, Kukkonen J (2013) A numerical model of birch pollen emission and dispersion in the atmosphere. Model Evaluation and sensitivity analysis. *International Journal of Biometeorology*, **57**:125–136.

IV
Sofiev M, **Siljamo P**, Ranta H, Rantio-Lehtimäki A (2006) Towards numerical forecasting of long-range transport of birch pollen: theoretical consideration and a feasibility study. *International Journal of Biometeorology*, **50**:392–402.

V
Siljamo P, Sofiev M, Severova E, Ranta H, Kukkonen J, Polevova S, Kubin E, Minin A. (2008) Sources, impact and exchange of early-spring birch pollen in the Moscow region and Finland. *Aerobiologia*, **24**:211–230.

SUMMARIES OF THE ORIGINAL PUBLICATIONS

The contents of papers I–V and the author's contributions are briefly outlined below.

I **Siljamo P**, Sofiev M, Ranta H, Linkosalo T, Kubin E, Ahas R, Genikhovich E, Jatczak K, Jato V, Nekovar J, Minin A, Severova E, Shalaboda V (2008) Representativeness of point-wise phenological *Betula* data collected in different parts of Europe. *Global Ecology and Biogeography*, **17**:489–503.

Paper I is dedicated to an analysis of available data on the phenology of the spring birch (the bud burst, the leaf unfolding and the start of the flowering). The phenological observations were collected from different sources and originated from different parts of Europe. All obtained data were quality-checked and converted into a unified database for further use in the parameterisation of the Thermal Time–type phenological model presented in Paper II. The primary concern with these observations was their suitability for parameterizing the emission module in the continental-scale atmospheric dispersion model. In particular, the representativeness of the observations is examined from several points of view. After the data analysis, the primary conclusion of the work was that a purely deterministic description of the pollen release term is inadequate, due to very high natural variability of phenological processes. Thus, it was necessary to include the uncertainty of the start of flowering in the pollen emission model presented in Paper II.

The author of this thesis was the main author of the publication. She processed the raw data, contributed to selecting the data analysis methods, performed the data analysis, and produced the bulk of the figure plots, except for the structure functions.

II Sofiev M, **Siljamo P**, Ranta H, Linkosalo T, Jaeger S, Rasmussen A, Rantio-Lehtimäki A, Severova E, Kukkonen J (2013) A numerical model of birch pollen emission and dispersion in the atmosphere. Description of the emission module. *International Journal of Biometeorology*. **57**:45–58.

Paper II presents the SILAM pollen modelling system, which describes pollen emissions and atmospheric dispersion to yield pollen concentrations. The paper presents the pollen emission module that was built within the SILAM model. The relationships between important weather parameters and pollen concentrations are analysed. It also estimates the parameters of the Thermal Time–type phenological model, which predict the start of the flowering. The main parameter of the birch forecasting system — the European temperature-sum threshold map for the start of flowering — is developed in this article.

The author of the thesis was responsible for estimating the temperature sum parameters. She participated in the planning of the emission module, provided vital contributions to the data analysis, collaborated in writing, and produced the bulk of the working-stage data plots and all maps. In particular, she made the section on the impact of weather parameters on pollen emissions and concentration.

III **Siljamo P**, Sofiev M, Filatova E, Grewling Ł, Jäger S, Khoreva E, Linkosalo T, Ortega Jimenez S, Ranta H, Rantio-Lehtimäki A, Svetlov A, Veriankaitė L, Yakovleva E, Kukkonen J (2013) A numerical model of birch pollen emission and dispersion in the atmosphere. Model evaluation and sensitivity analysis. *International Journal of Biometeorology*, **57**:125–136.

Paper III presents the evaluation of the SILAM pollen modelling system from various points of view. The subjects of interest are how useful the model is for specific tasks related to pollen forecasting, public health applications, and related tasks. The paper analyses the sensitivity of the start of the flowering on the source of the temperature sum threshold map (i.e., the pollen observations vs. the phenological observations). The impact of selecting a specific numerical weather prediction model (NWP) on the quality of the pollen predictions, as well as the regional peculiarities of the forecasts, are analysed as well.

The author of this thesis is the main author of the publication. She planned the analysis and performed all of the model experiments. She was responsible for estimating the temperature sum parameters presented in the paper. She planned and performed the model evaluation. All of the figures were plotted by the author.

IV Sofiev M, **Siljamo P**, Ranta H, Rantio-Lehtimäki A (2006) Towards numerical forecasting of long-range transport of birch pollen: theoretical consideration and a feasibility study. *International Journal of Biometeorology*. **50**:392–402.

Chronologically, **Paper IV** was the first paper written within this study. It considers whether forecasting long-range pollen transport is possible at all. It theoretically examines the possibilities of how pollen grains can be transported by atmospheric flow and their ability to follow turbulent eddies. It presents a feasibility study of long-range pollen transport modelling and outlines the directions of model development. It also presents the first version of the European birch habitat map, as well as the pollen source areas responsible for several long-range transport episodes in Finland. The first attempts to predict pollen concentrations are also presented in this article.

The author of this thesis performed and analysed all of the model experiments. She was responsible for deriving the European birch habitat map. She plotted parts of the figures and collaborated in writing. She participated in planning the long-range pollen transport forecasting system.

V **Siljamo P**, Sofiev M, Severova E, Ranta H, Kukkonen J, Polevova S, Kubin E, Minin A (2008) Sources, impact and exchange of early-spring birch pollen in the Moscow region and Finland. *Aerobiologia*, **24**:211–230.

Paper V investigates specific episodes of long-range pollen transport in north-eastern Europe and specifies the source areas of such episodes. The main focus is on the source areas of the pollen observed in Moscow before the start of flowering and on the possible linkages to early pollen observations in Finland.

The author of this thesis was the main author of the publication. She selected the cases to be studied and performed all of the model runs. She plotted all of the figures and analysed the cases heavily.

1 INTRODUCTION

It is a beautiful early spring day. A gentle south wind blows. Suddenly, itchy eyes violate your good mood, and your nose starts to run. What? Already? There is still some snow on the ground. Pollen can't be in the air, can it?

Birch pollen grains are observed fairly regularly before local flowering starts in Northern Europe. Sometimes, the levels are so high that people have allergic symptoms. Where are the sources of early spring pollen located? Are they long-range transported (LRT), and from how far? And, most importantly, how can we predict such pollen episodes beforehand?

The original goal of this study was to produce a forecasting system for birch pollen LRT for Finland. However, as the work progressed, it became clear that pollen does not know national boundaries. Thus, we have to generate a European-wide bio-physical numerical prediction system for birch flowering and pollen dispersion.

In this thesis, we aim to answer the following key research questions:

- Is it possible to forecast long-range pollen transport? What do we need to do so? (Papers II and IV, Section 2)
- What are the features of the phenological data, and what can we learn from them? (Paper I, Section 3)
- From where do LRTed pollen grains come from and under which conditions does it happen? (Papers IV and V, Section 4)
- How does one predict birch pollen emissions and concentrations using atmospheric dispersion models? (Paper II, Section 5)
- How effective are numerical pollen forecasts? (Paper III, Section 6)

This study does not include such topics as pollen and climate change, pollen and its health effects, pollen and air pollution, or pollen and allergens. We also did not consider local transport of pollen grains. All these fields are relevant for future studies, and the regional numerical pollen dispersion model could serve as a new tool for their benefit.

Birch was selected for this study because it is an important allergy plant (WHO 2003, D'Amato et al. 2007). Up to 10–20% of Northern and Central Europeans are sensitized to birch pollen (e.g., WHO 2003, D'Amato et al. 2007, Jantunen et al. 2012, Myszkowska 2013). Birch pollen grain is also prone to long-range transport.

Two common species of tree-like birch grow in Europe: silver birch (*Betula pendula*) and downy birch (*Betula pubescens*). In addition, the shrub-like dwarf birch (*Betula nana*) grows in northern and mountainous areas. Silver Birch is also a commonly-used park and ornamental tree. The pollen from silver birch and downy birch are usually not differentiated from each other.

Birch pollen grains develop inside catkins. The average number of catkins in one tree in southern and western Finland is about 800, although the annual variability is large (from less than 100 to up to 1,500 male catkins/tree) (METLA 2013). Erdtman (1943) approximated that one *Betula pubescens* catkin can produce 6 million pollen grains.

A birch pollen grain is 20–29 µm in diameter and is relatively light (a dry pollen grain is ~800 kg/m^3) (Erdtman 1943). In the atmosphere, grains can dry out and become wet again. Thus, their weight varies with the amount of moisture (Erdtman 1943). It is also possible that a small, submicronic protein particle — the so-called allergen that causes allergic symptoms — can slip out from a pollen grain (Rantio-Lehtimäki et al. 1994, Madeja et al. 2005, Buters et al. 2012). However, the mechanisms of this process are still relatively unknown; thus, it has not been included in our pollen dispersion model.

The LRT of pollen has been known for a long time, since Erdtman (1937) reported observing pollen grains over the Atlantic Ocean. In spite of this, the possibility that pollen can be transported over long distances in substantial amounts has long been debated within the scientific community. As a particle to be transported in the atmosphere, a pollen grain is quite large, even with respect to its light weight. Thus, the majority of pollen grains stay near their source area (Hyde and Williams 1944, Wright 1952, Raynor et al. 1970, Tampieri et al. 1977). However, most of the older pollen dispersal studies assumed neutrally stratified atmospheric conditions. Jackson and Lyford (1999) proved that pollen dispersal is likely to occur under unstable conditions, in which pollen is transported more widely than under neutral conditions.

Pollen concentrations are usually high near their source, but — contrarily to most other atmospheric pollution cases — low concentrations are also relevant. Small amounts of pollen can cause allergic rhinitis in the most sensitized persons (Viander and Koivikko 1978, Jantunen et al. 2012). For example, 10 000 grains/m^3 around the source can dilute to 50 grains/m^3 about 200 km from the source (i.e., only 0.5% of the original concentration), yet it may still affect allergic persons.

Often, LRTed pollen counts are fairly small (less than 10 grains/m^3), and they merely raise a question about the origin of these pollen grains. However, the concentrations can sometimes be quite abundant (e.g., Ranta et al. 2006), and thus, LRTed pollen can cause allergic symptoms in people (Hjelmroos 1992, WHO 2003, D'Amato et al. 2007). Therefore, it would be very beneficial to predict such events early enough for allergic persons to prepare themselves in time. In addition, long-range pollen transport can slightly affect gene flow and plants' adaptation to climate changes (Paper V, Kremer et al. 2012). There is also academic interest in assessing how such a large particle as a pollen grain can be transported far away from its source (Paper IV, Jackson and Lyford, 1999).

Schematically, the processes and interactions affecting the passively transported biological substances include (see Figure 1.1) the presentation of biological material, its release into the atmosphere, dispersion, transformation, deposition, and impact (Sofiev et al. 2013). Sometimes, after deposition, the grains can be subjected to refloating processes and thus become resuspended back into the air. In the SILAM model, resuspension is not taken into account, although discussions on its importance are on-going.

This thesis is organised as follows. The second section presents a review of previous numerical pollen simulations and briefly describes the SILAM pollen forecasting system and challenges within it. Numerical pollen simulations at the regional and continental scales are a fairly new field of research, and only a few applications have been published in the literature (Kawashima and Takahasi 1995; 1999; Hidalgo et al. 2002; Van de Water et al. 2003; Helbig et al. 2004; Pasken and Pietrowicz 2005, Paper IV; Schueler and Schlünzen 2006; Vogel et al. 2008; Efstathiou et al. 2011; Zink et al. 2012; Paper II).

In this study, the necessary components for pollen LRT forecasts were collected piece-by-piece. After contemplating the entire modelling chain, components that were already available were used, whereas missing or low quality components had to be

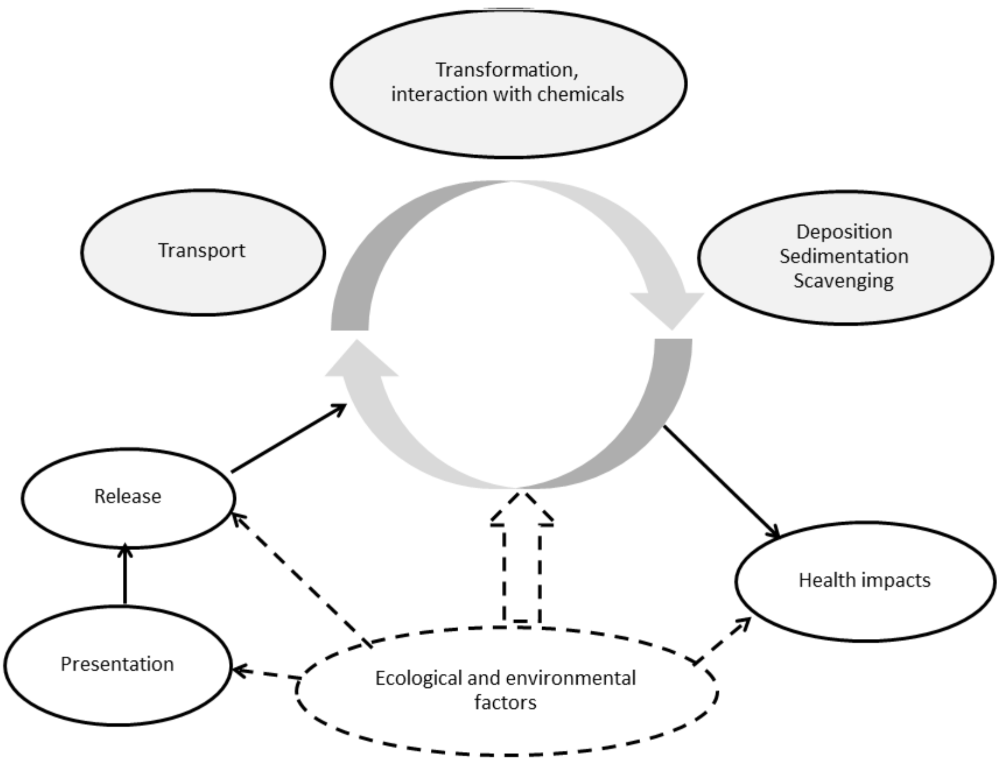


Figure 1.1 *Phases of aerobiological processes related to transport of chemically inactive biogenic aerosols (Sofiev et al. 2013, extended from Isard and Gage 2001)*

developed. The dispersion modelling system SILAM was developed at FMI (Sofiev et al. 2006), and aerobiological and meteorological data were obtained from existing databases. The rest had to be developed by us, including the birch habitat map (Paper IV, Section 3.1), temperature sum thresholds for Europe (Papers II and III, Section 5.2), and the pollen release model (Paper II, Section 5.3).

After this review, the tools and data used to develop the model and its applications are presented in greater detail in the third section. In particular, we collected and analysed phenological data for birch flowering starting time predictions (Paper I, Section 3.2).

Several backward trajectory studies were performed to delineate the potential source areas in the 2000s (e.g., Hjelmroos 1991; Rousseau et al. 2005; Mahura et al. 2007; Stach et al. 2007; Skjøth et al. 2007, 2008a, 2009; Smith et al. 2008; Hernandez-Ceballos 2011). More advanced inverse dispersion studies were carried out during this study (Papers IV and V, Ranta et al. 2006; 2011; Veriankaitė et al. 2010). The fourth section focuses on tracking back the source areas of LRTed pollen in North-Eastern Europe (Papers IV and V).

The primary challenge was developing a pollen emission module for this early-spring flowering tree (Papers II). Pollen emissions must contain the locations of the source areas, the start and end of flowering, as well as of pollen release from the catkins. The fifth section is dedicated to the emission modelling. Finally, in the sixth section, the SILAM pollen modelling system is evaluated against pollen observations in the spring of 2006 (Paper III, Section 6.2).

2 NUMERICAL POLLEN SIMULATIONS

Active interest in numerical pollen dispersion forecasting has only existed since the start of this millennium. Forward pollen modelling studies are not numerous, and most of them focus on the local transport of pollen and seeds (e.g., Jarosz et al. 2004; Aylor et al. 2006; Arritt et al. 2007; Kuparinen et al. 2007). Their main target has been on genetically modified organisms (GMO), such as crops, and the possibility that these GMOs may escape to more pristine areas. Nevertheless, some simulations of regional and long-range transport of pollen grains have also been performed. They can be divided into case studies and pollen season simulations.

Case studies

Van de Water et al. (2003) simulated two mountain cedar pollen seasons in Oklahoma, USA with the HYSPLIT trajectory model. Pasken and Pietrowicz (2005) simulated oak pollen dispersion using a combination HYSPLIT–MM5 model in Missouri, USA, in April 2000. The emissions themselves were kept constant or were very roughly modelled in these studies.

Helbig et al. (2004) created detailed pollen emission and resuspension terms for the KAMM/DRAIS model system. Their study covered an area of 250 km × 250 km located in Germany. Despite possessing detailed pollen emissions, they did not try to simulate a real case, but theoretically investigated pollen emissions and transport. Their 3D-simulation results showed a remarkably wider influence of pollen sources than expected, based on their 1D simulations.

Later, Vogel et al. (2008) also made dedicated efforts to simulate birch pollen concentrations in Switzerland using the COSMO-ART model, which included pollen emissions from Helbig et al. (2004). They only computed the single case of April 19–22, 2006, and thus avoided forecasting the start of flowering.

Schueler and Schlünzen (2006) simulated oak pollen dispersion using the METRAS model. Their main interest was only one oak stand, and they only simulated a few typical days, rather than the whole flowering period. Their system included an emission module that takes into account the flowering stage. They assumed that only humidity affects actual pollen production.

Zink et al. (2012) modelled ragweed pollen release and dispersion with the COSMO-ART NWP system for Central Europe. They also used the emission parameterizations of Helbig et al. (2004) and Vogel et al. (2008). As they simulated only one case in 2006, they did not need to predict the start of flowering.

Pollen season simulations

While none of the above pollen case studies tried to predict the start of pollination, alternatively, Kawashima and Takahasi had already performed Japanese cedar simulations in 1995 and 1999 that coupled emissions and dispersion. They analysed and simulated earlier pollen cases, but they did not try to make predictions. For emissions, they used a Japanese cedar map. The start of flowering was simulated using the temperature sum or a fixed date, and the length of pollination was fixed at 10 days. Weather parameters were allowed to affect pollen release. Simulations were made with an Eulerian dispersion model and actual weather observations. The simulation based on the temperature sum map reproduced pollen concentrations well, but without it, the pollen season was too long, and the highest peaks were not caught.

Hidalgo et al. (2002) predicted olive pollen concentrations over a 200 km × 200 km area in Spain. They used the CALPUFF dispersion model with emissions based on an olive tree map, the temperature sum predicting the start of flowering, and a neural network simulation for the daily and yearly variations. The preliminary results were promising, but the method still needs more testing.

Efstathiou et al. (2011) simulated birch and ragweed pollen emissions and dispersion in the USA using the NWP model MM5, coupled with the air quality model CMAQ. The structure of their modelling system has clear analogies with the SILAM modelling system presented in this study. Their simulation for the case of birch covered April 2002. Their emission term is based on the pollen release developed in Helbig et al. (2004), with some modifications based on the emissions scheme presented in Paper II and Section 5.3. The start of flowering was also predicted using the temperature sum approach.

The SILAM pollen forecasting system

Paper IV (2006) was the first attempt to simulate birch pollen dispersion over Europe using the SILAM dispersion modelling system. The start of flowering was based on climatological averages from Rötzer and Chmielewski (2001), and pollen release was kept independent of weather conditions.

Conversely, Paper II (2013) presents a more advanced birch pollen emission scheme using the SILAM model. The source area is about the same as in earlier studies, but the start of flowering was predicted using the thermal time–type phenological temperature sum model and allowed several weather parameters to affect pollen release. Figure 2.1 shows a schematic picture of the current SILAM pollen modelling system.

The SILAM dispersion modelling system (Sofiev et al. 2006; Sofiev et al. 2008) uses the meteorological information obtained from numerical weather prediction (NWP) models. Additionally, for pollen simulations, a European birch habitat map (Paper IV, Section 3.1) and temperature sum thresholds for Europe (Papers II and III, Section 5.2) are used as input information for the SILAM model. Inside the model, the pollen emission algorithm (Paper II, Section 5.3), which itself needs information from the NWP model, calculates pollen release from catkins. Once dispersion computations start, the weather parameters also control the transport, transformation, and removal processes of pollen grains (Paper IV). As a result, the model produces birch pollen concentration maps for Europe (Papers III, IV, and V, Section 6). The automatic, daily SILAM birch pollen concentration forecasts are presented in at the website http://silam.fmi.fi.

Figure 2.2 shows the development of the pollen model. Since birch pollen can be transported in the atmosphere for hundreds and, under favourable conditions, more than thousands of km, a birch habitat map that covered all of Europe was needed (Paper IV, Section 3.1). It was developed using existing tree species data (Köbler and Seufert 2001) and the European Forest Institute's (EFI) maps, which has been produced using satellite information and forest inventories (Päivinen et al. 2001; Schuck et al. 2002). Unfortunately, the EFI's data set does not include birch as a separate tree, but as parts of broadleaf, mixed, or conifer forests. However, the EFI's maps were needed to supplement Köbler and Seufert's (2001) dataset, which did not cover all the necessary areas. In particular, Russian birch stands, which are important pollen sources, were missing. Thus, we had to estimate the fraction of birch from the EFI's dataset for the missing areas.

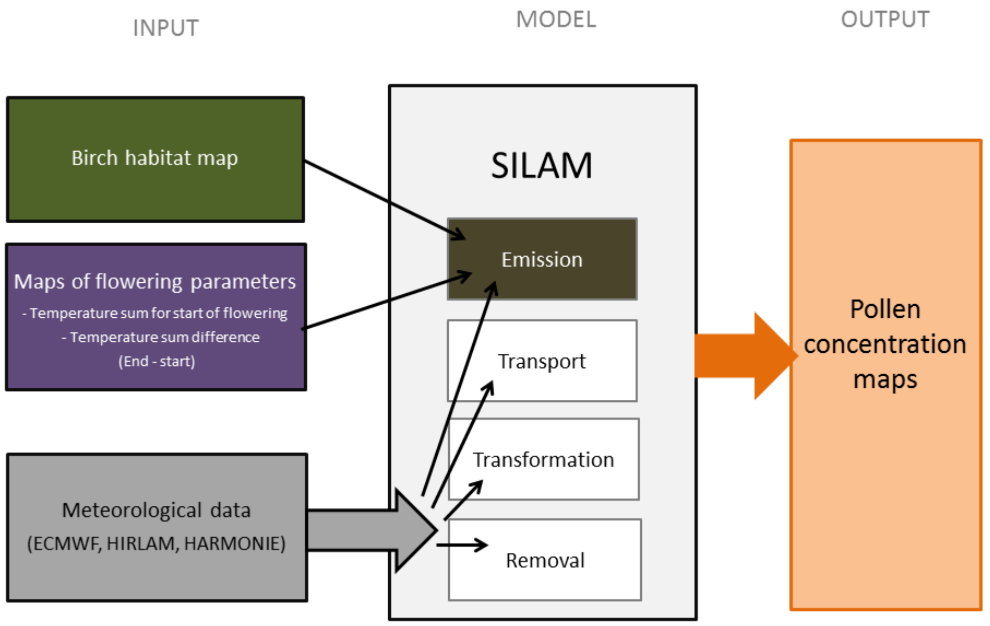


Figure 2.1 *The SILAM pollen model system applied in Papers III, IV, and V. Topics in the colour-coded boxes are covered in this study in more depth.*

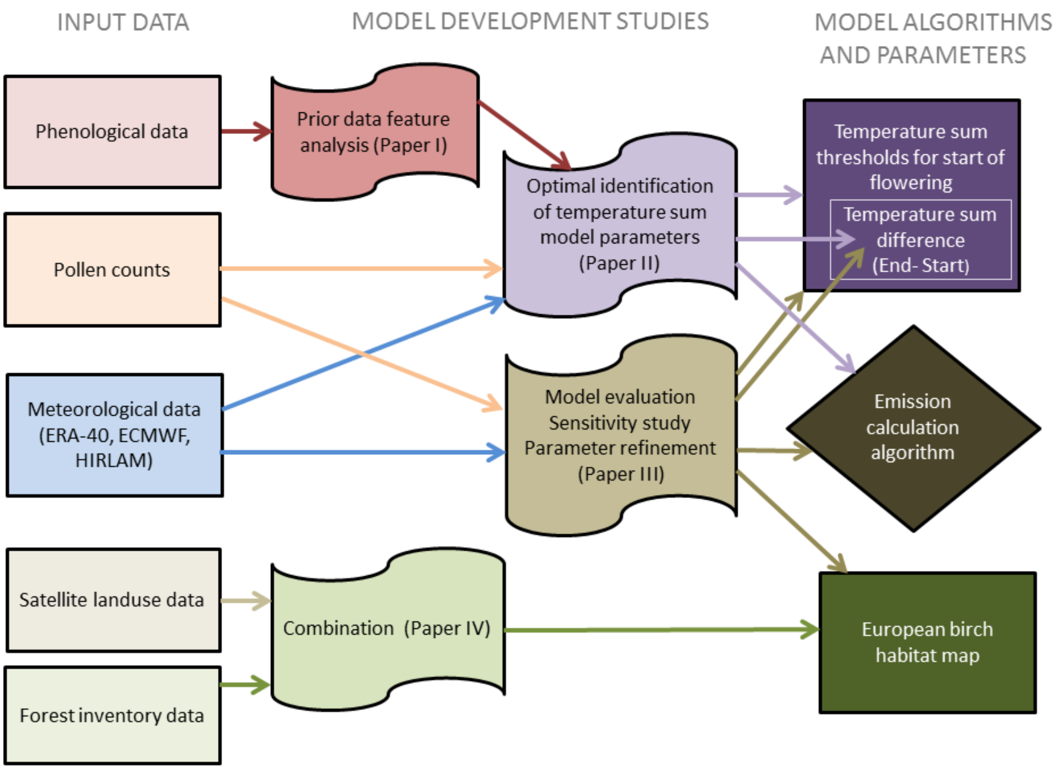


Figure 2.2 *Schematic presentation of the building up of the SILAM pollen model components*

Phenological observations throughout Europe were also needed, since they are important input information for phenological models that predict the start of flowering. So far, no phenological models are able to predict the phenological events throughout Europe, since the parameters of these models are site-specific (Schaber 2002). At the beginning of the study, the European phenological database (a product of COST Action 725) had not yet been published. Therefore, the data about birch bud burst, leaf unfolding, and start of flowering were collected country-by-country. These data are analysed in Paper I (Section 3.2).

A simple thermal time–type linear temperature sum model (e.g., Linkosalo et al. 2008) was selected to predict the flowering start time (Papers II and III, Section 5.2). We calculated the model parameters for Europe using phenological data collected during the study and pollen observations from the European Aeroallergen Network (EAN).

Pollen release from catkins is affected by several weather parameters (e.g., Stach et al. 2008; Puc 2012). The model algorithm and the impact of weather parameters on pollen release are presented in Paper II (Section 5.3). Moist air and rain slow down or prevent pollen release into the air, while warm, windy, and gusty weather favours pollen release. In the current SILAM model version, the so-called “open pocket” principle is assumed, i.e., that pollen is released as long as there are some pollen grains left in the catkins.

The SILAM pollen model is evaluated and its sensitivity to different NWP models and different temperature sum maps are studied in Paper III (Section 6). These studies contributed to the birch habitat map, the pollen emission algorithm, and the temperature sum thresholds.

3 TOOLS AND DATA FOR MODEL DEVELOPMENT AND APPLICATIONS

This chapter describes the tools and data used in the study. We describe how the European birch habitat map (Paper IV) and phenological data collected during the study, with their representativeness, were produced (Paper I). We also introduce data from existing databases, e.g., the European Aeroallergen Network (EAN) pollen data and the NWP model data. The atmospheric dispersion model SILAM (Sofiev et al. 2006, 2008) used in this study and its settings are also presented.

3.1 BIRCH HABITAT MAP

The distribution area of silver birch extends from the mountainous Mediterranean regions (excluding Greece and the Iberian Peninsula) up to about 70º latitude and across Eurasia, from the British Isles to the Pacific Ocean (Mitchell and Wilkinson 1997; Vakkari 2009). Downy birch is a slightly more northern species, and its subspecies, the mountain birch, grows in Lapland up to the Arctic Ocean. In Northern Europe and Russia, birch is a common tree species in mixed forests, but pure birch groves can also be found. In Western and Central Europe, its distribution is more fragmented, and more southern birch trees grow mainly in mountainous areas, such as the Pyrenees. The silver birch is a common ornamental tree in Europe, and Pauling et al. (2012) even assumed that ornamental birches cause more pollen exposure than natural birches in Switzerland.

Although the need for numerical pollen forecasts was recognized long ago, active model development only gathered pace in the 2000s. For the sake of this task, vegetation maps were prepared for the birch (Paper IV, Skjøth et al. 2008b, Vogel et al. 2008, Pauling et al. 2012), alder (Helbig et al. 2004), oak (Schuler and Sclünzen 2006), cedar (Kawashima and Takahashi 1995, 1999), and olive trees (Hidalgo et al. 2002), as well as ragweed (Zink et al. 2012). Producing vegetation maps for pollen predictions incurs specific challenges for each species or plant. For instance, although birch is a wild forest tree that mainly grows in mixed forests, it is also a common ornamental tree. Generally, tree species maps are based on forest inventories and satellite data (Skjøth et al. 2012), and they do not take ornamental trees into account (Pauling et al. 2012). Therefore, Pauling et al. (2012) used pollen observations to complement forest inventories, while Skjøth et al. (2008b) compared satellite data and forest inventories for the pollen index maps of corresponding species. However, they pointed out that the pollen observation-based source maps are easy to produce but susceptible to many errors.

In general, pollen model simulations do not usually use continent-wide tree species data; rather, they used to model pollen sources over small areas (e.g., Kawashima and Takahasi 1999; Schueler and Schlünzen 2006), over one country (e.g., Vogel et al. 2008), or a few countries, such as Central Europe (Zink et al. 2012). The birch map for the SILAM model simulation was the first to be compiled for the whole of Europe, including most of the European part of Russia (Paper IV).

Development of the European birch fraction map for the SILAM model

Modelling and predicting the long-range transport of birch pollen requires that the source areas, i.e., the birch habitats, be quantified and mapped (Paper IV). For the

SILAM model, the compilation of the European birch map was based on two datasets. We used Köbler and Seufert's (2001) tree species maps in this study. They collected data on a very fine grid (1 km x 1 km) for 115 tree species. From this material, we extracted information on the growth areas of downy birch (*Betula pubescens*) and silver birch (*Betula pendula*). Unfortunately, as the information had been collected separately from different countries, it was not of uniform quality, and the species were not always well-segregated. Therefore, the information was combined into one general-birch map. In reality, the phenology of the different birch species differs somewhat (Sarvas 1955; Luomajoki 1999). However, the error induced by this combination is small, compared to other inherent uncertainties in the modelling exercise, and it can be partly compensated for by broadening the temperature sum window for the start of pollination. Köbler and Seufert's (2001) data do not cover the whole of Europe; for example, information from Russia is missing entirely. Moreover, information from some countries, such as Great Britain, Estonia, and Denmark, did not seem reliable, so we did not use the data from these areas. Later, Brus et al. (2011) published new tree species maps for Europe; however, this dataset was not included in this study.

Fortunately, forest maps from the European Forest Institute (EFI) (Päivinen et al. 2001; Schuck et al. 2002) were found to supplement these missing areas, but in EFI's satellite-based maps, only broad-leaved forests, mixed forests, and conifer forests were presented. We estimated the fraction of birches in forests, assuming that the fraction of birches in missing areas was the same as in neighbouring areas with explicit data available from the above-described tree-species inventory. Later, in Central European areas, we partially replaced the data with those from the EFI, because the simulations showed that the SILAM found annual pollen concentrations in Central Europe that were too low. Figure 3.1 shows the first version of the European birch map for the SILAM simulations (Paper IV), while Figure 6.3 is a slightly edited version used for a model evaluation of the SILAM dispersion modelling system (Paper III).

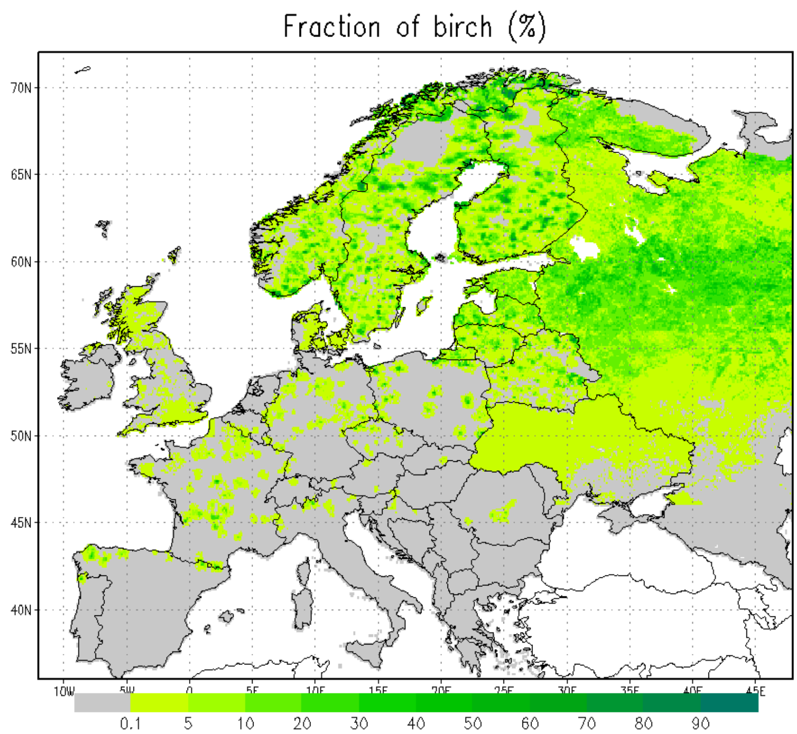


Figure 3.1 *First version of the birch fraction map, with 0.1º resolution*

3.2 PHENOLOGICAL DATA

Phenological observations — the dates of leaf bud burst, leaf unfolding, and start of flowering — are one of the most important sources of information on the physiological condition of plants and their reactions to external forcing (Sparks and Carey 1995; Sparks and Menzel 2002; Menzel et al. 2006). Consequently, during the last decade or two, there have been a quickly growing number of studies using these data to evaluate the integrated characteristics of climate and its changes (Heikinheimo and Lappalainen 1997; Parmesan and Yohe 2002; Chen et al. 2005; Crepinsek et al. 2006). These data are also used for the development, parameterization, and evaluation of various (semi-) empirical models of phenological phases (e.g., Häkkinen et al. 1998; Chuine 2000; Linkosalo 2000; Rötzer and Chmielewski 2001; Schaber and Badeck 2003). A significant limitation of phenological archives is that their features vary between different countries. For instance, many European regions are represented by only a few monitoring sites.

At the time of research, there was no single database in Europe from where phenological birch flowering or leaf unfolding data could be obtained. Therefore, the data presented in Paper I were collected country-by-country from all over Europe. The collected data were screened for quality and converted into a single database. This database contains data from 15 countries. The database records the bud burst, leaf unfolding, and start of flowering. The largest number of entries is for the date of the leaf unfolding, which was reported by all countries. Altogether nearly 60,000 leaf unfolding observations were collected, the data for the start of flowering were about half of that, and bud burst observations were present in barely more than 10% of the records.

The lengths of the time series also vary from country to country. The German observational network is dense, and the time series are long. In the UK, the observation series may cover only 1–2 years from one station, but the observation network is very dense. The longest single observation series was from Russia (more than 30 years), but the observation network is fairly sparse there.

The representativeness of the observations can be affected by a single plant, the local climate, such as a warm south slope or the presence of a cold lake, and specific local weather conditions. Furthermore, the inadequate observation frequency and human mistakes by the observer can be sources of errors. In this study, only the most evident mistakes were removed. Therefore, we mainly examine the representativeness of the leaf unfolding observations in this work. Most countries did not classify which birch species the data stand for.

After this study, in 2009, the COST-725 action ("Establishing a European Phenological Data Platform for Climatological Applications") published a database containing phenological data from several European countries. PEP725 (PAN 2011) is the successor of the COST action and contains *Betula* data from 122 stations in 23 European countries. Most of its data are from the years 1971–1991.

Representativeness of the phenological birch observations in Europe

The main task of the collected phenological data (Paper I) was to act as inputs for the phenological model that describes the start of flowering in Europe (Papers II and III). Therefore, our main interest was in a grid-type representation.

Several mechanisms limit or promote the synchronization of space-separated biological systems and, consequently, the representativeness of single-site observations. One of the most important mechanisms is a large-scale forcing by meteorological and geophysical factors. From the theory of differential equations, it is known that the evolution of linear systems under external forcing will generally follow the evolution of the forcing, which works as a synchronising agent for these systems. In population dynamics and ecology, this is referred to as the Moran effect (after the pioneering study by Moran in 1953). Numerous studies (e.g., Blasius and Stone 2000; Ripa 2000; Engen and Sæther 2005; Sparks and Braslawska 2001) have shown that the Moran effect plays a crucial role in the spatial synchronization of biological systems. For pollen and seed production from trees, Koenig and Knops (1998; 2000) demonstrated that synchronous seed reproduction over large areas in the northern hemisphere is caused by a common environmental fluctuation, such as rainfall and temperature.

From an evolutionary point of view, the effective pollination of anemophilous plants requires adaptations that cause scattered individuals to release pollen at the same time over large areas. For wind-pollinated Betulaceae trees, the benefits of releasing a great amount of pollen at the same time seem obvious: an exponential positive relationship exists between the amount of pollen production, pollination efficiency and seed viability (Sarvas 1952; Shiabata et al.1998).

The purpose of Paper I was to provide a quantitative assessment of the spatial representativeness of phenological observations in Europe using the birch (*Betula*) taxon as an example. There, we also demonstrated how a representativeness assessment can be used as a quantitative indicator of the variability of phenological processes and their spatial and temporal scales.

Spatial variability

Birch leaf unfolding happens first in Southern and Western Europe and then proceeds towards the north-east. The variability is the largest in a marine climate and smallest in a continental climate (Figure 3.2). In other words, the variability is the largest over areas in which the leaves first unfold, whereas the variability becomes smaller in areas where leaves unfold last.

A possible explanation for such behaviour could be linked to climate. Under a marine climate, the temperature sum gradually accumulates nearly all the time, in contrast to a continental climate, where the temperature sum does not accumulate at all for a long time, but rises quickly when it eventually begins to accumulate. This gives a strong signal to the plants to start their growing season. In a marine climate, the accumulation of the corresponding temperature sum will take longer; thus, differences between individual trees became more visible. This way, the plants do not react simultaneously to the stimulus.

The variability of phenological observations is large, regardless of resolution (Figure 3.3). In practice, it is from one week to two weeks. The variability barely grows at all, even if the grid size increases. Only at extremely large grid sizes does the variability increase distinctly.

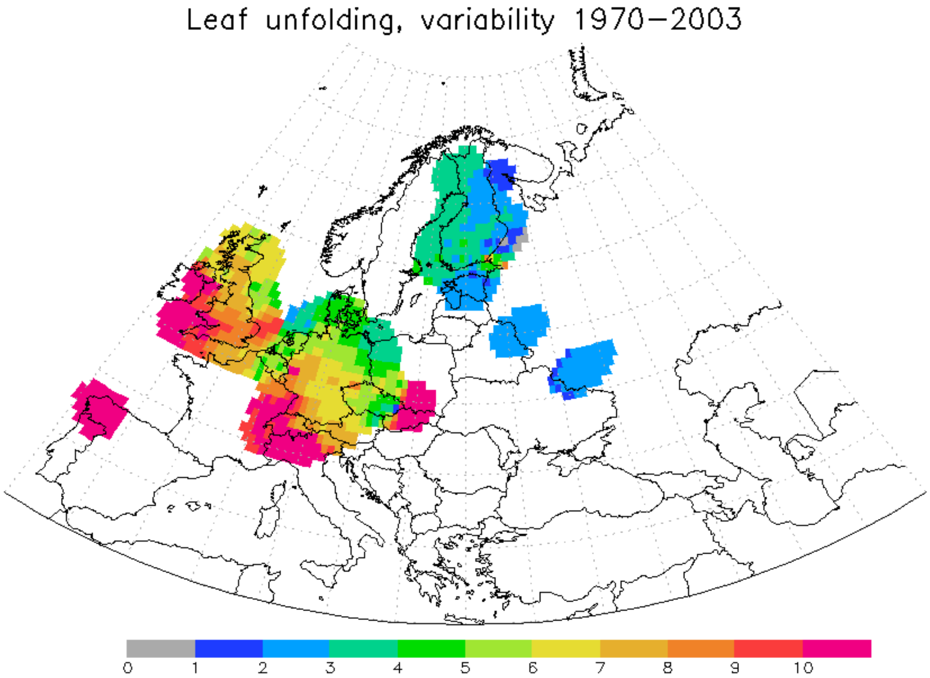


Figure 3.2 *Mean variability (days) of Betula leaf unfolding upon the ERA-40 grid (1.125º × 1.125º) based on available data, after screening for quality and representativeness (Paper I)*

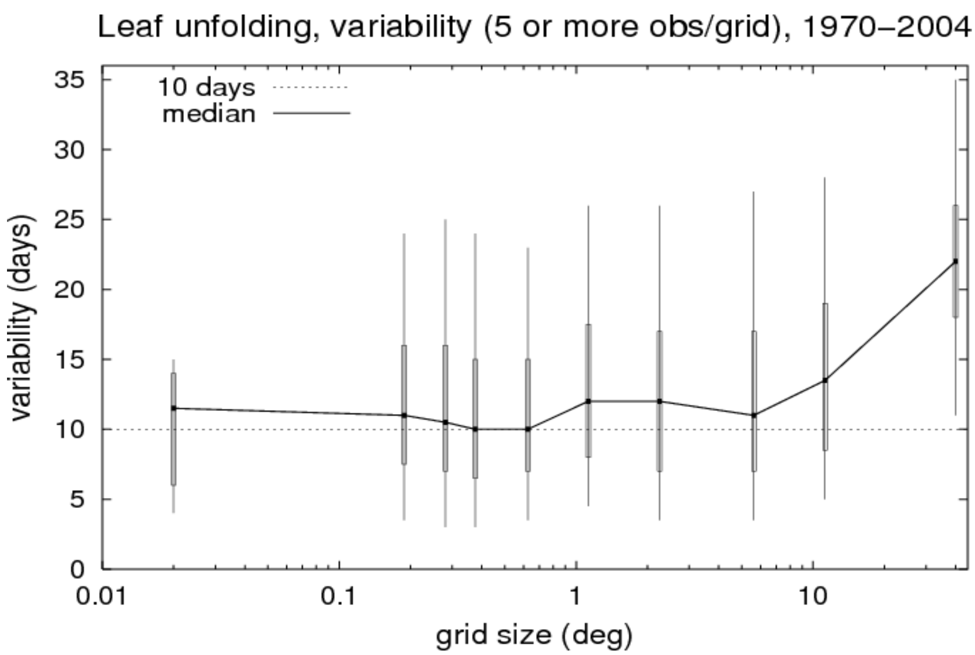


Figure 3.3 *Variability of leaf unfolding within quadrants (all stations in 1970–2004 with five or more observations per grid) aggregated into grids with different resolutions. The plot displays the median (solid line), upper and lower quartiles (thick vertical), and 5th and 95th percentiles (thin vertical bars) of variability (Paper I)***.**

Influence of local climate and topography

Analysing the influence of local climate and topography requires long time series and a dense network, and was thus almost solely based on observations from Germany. The working hypothesis was that local climate should create a spatially random but temporally synchronised bias for a specific station, whereas the influence of meteorological processes would be much more synchronised in space and random in time. Micro-scale noise from individual trees and non-perfect observations were additional independent components to those above and were assumed to have similar features for all stations within a specific grid cell.

The above two factors could be distinguished by analysing the ability of single stations to follow regional averages year by year. For areas having a sufficient network density and a long observational history, it appeared possible to "label" each station in accordance with its behaviour —"early", "representative", "late", and "random"— and to perform this labelling for all grid resolutions. A station was classified as belonging to a specific group (i.e., early, representative, or late) if it fell into this group in 70% of the cases. The expectation was that the fraction of "representative" stations increases as resolution becomes finer. This trend would reveal the impact of local climate.

In our analysis, a station was called "representative" if it corresponded to the median of the area (median ± 2 days). Thence, a "late" station would be systematically late nearly every year (> 2 days from median), and an "early" station would correspondingly be systematically early (> 2 days from median). A "random" station, on the other hand, would not regularly match any of the other groups.

The result of the analysis — the fractions of stations in each category in relation to the grid resolution — is shown in Figure 3.4. As expected, the smaller grid cell sizes corresponded with a higher fraction of "representative" stations because the corresponding micro-climate processes were resolved by using these grid sizes. The number of "early" and "late" stations decreased monotonously with grid size, which also pointed to local climate specifics as the primary reason for such systematic bias. The number of "random" stations is very high and did not change much, indicating that their uncertainties were not connected with spatially-organised phenomena. Such stations tended to deviate randomly from any neighbouring site, regardless of the distance between them.

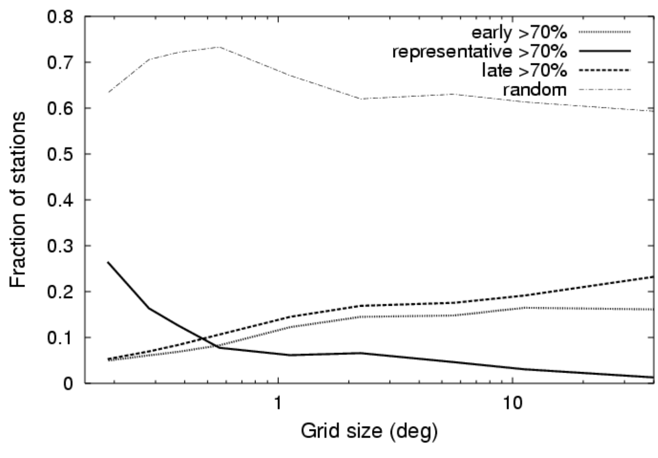


Figure 3.4 *Fractions of "early", "late", "representative", and "random" phenological stations, with regards to leaf unfolding as a function of the mean grid cell size (Paper I)*

3.3 AEROBIOLOGICAL DATA

Regular birch pollen observations are available from the European Aeroallergen Network (EAN), which receives data from about 35 countries and 300 sites. Pollen observations began in 1974, although the bulk of the data was collected after 1985.

In this study, pollen observations were used for two different purposes: 1) twenty years of pollen data (1980–2000) were combined with the phenological data to estimate the temperature sum threshold for the first flowering date (Section 5.2, Paper III) and 2) the 2006 dataset was used to verify the SILAM dispersion results (Section 6.2, Paper III).

We used the 2.5% criterion to determine the temperature sum threshold for the first flowering date in Paper III, i.e., the flowering season was supposed to start as soon as the cumulative birch pollen count reaches 2.5% of the annual sum for the specific year (Goldberg et al. 1988). The end of the flowering season followed the 95% criterion: the flowering season is assumed to be finished when the sum reaches 95% of the annual total pollen (Goldberg et al. 1988).

The 2.5% criterion proved to be too low for Northern Europe, due to the significant impact of pollen LRT at the beginning of the pollen season (Ranta et al. 2006; Veriankaitė et al. 2010). Therefore, a 5% criterion was used for the starting date to evaluate the SILAM flowering season predictions (Paper III). It allowed for a more effective filtration of LRT episodes at the beginning of spring.

Since all the above criteria require integrating the observed pollen time series, the data from an EAN station had to be sufficiently uniform (Paper III). This completeness requirement reduced the number of included stations by about 25%. For 2006, for instance, the evaluations of 155 stations on the start and end of flowering were included, out of 213 stored in the archive. On the other hand, the evaluation of pollen concentrations from the model did not require any station filtration, and only those SILAM predictions for which the observations exist were used.

3.4 METEOROLOGICAL DATA

Two main sources of meteorological information were used for both forward and inverse (footprint) pollen simulations. The HIRLAM (versions 6.2.1 and 6.3.7) NWP model (Unden et al. 2002) is a so-called limited area model that spatially covers all of Europe and has a forecast head time of up to 54 hours. Its resolution is about 20 km. The ECMWF's (European Centre for Medium Range Weather Forecasts; www.ecmwf.int) global NWP model was also used. Its physics and horizontal resolution depend on the year. In early simulations, the grid size was about 75 km or 40 km and about 25 km later. Short-term forecasts were always used, i.e., +3 h and +6 h forecast with HIRLAM and from +3 to +12 h for ECMWF-based simulations.

The ECMWF's ERA-40 analysis data (Uppala et al. 2005), which go back in time for more than 40 years, were used to estimate the parameters necessary for the thermal time phenological model (Papers II and III). The key parameter from the ERA-40 data was the temperature at two meters above the ground. The resolution of the ERA-40 analysis data is 6 h and 1.125º (~120 km).

3.5 THE SILAM ATMOSPHERIC DISPERSION MODEL

As shown in Paper IV, virtually any comprehensive chemistry transport model can be used to describe pollen dispersion after their release from catkins: advection with the main flow, mixing due to turbulence, gravitational settling (the main mechanism of pollen dry deposition), and scavenging with precipitation. The pollen model presented in this study was constructed as a part of the SILAM modelling system (Sofiev et al. 2006; Sofiev et al. 2008). The model's dynamic core includes both Lagrangian (Sofiev et al. 2006) and Eulerian (Galperin 2000; Sofiev 2002) advection/diffusion formulations. The removal processes are described via dry and wet deposition. Dry deposition of pollen is described via gravitational settling, which, for birch pollen, yields at the characteristic dry deposition velocity of ~1.2 cm/s (Paper IV). The SILAM wet deposition parameterization (e.g., Sofiev et al. 2006) is based on direct observations performed for moderately hydrophobic aerosols, although, in reality, particles can dry out and become wet when transported in the atmosphere (Erdman 1943).

In this study, both the Lagrangian (Papers IV and V) and Eulerian (Papers II and III) versions of the SILAM model are used. Both versions were executed with a time step of 15 min. The Lagrangian particle simulations assume a well-mixed atmospheric boundary layer and fixed diffusion intensity in the free troposphere. Following the standard procedure of Monte Carlo Lagrangian particle models, turbulent mixing is represented via random relocation of a large number of particles (10,000–20,000) released for each case. The Eulerian system is configured to include 10 vertical grid layers up to a height of 4 km above the ground. The horizontal grid cell size is 20–30 km, and the domain of simulations covers almost all of Europe.

The so-called "source term" of the footprint simulations consisted of the actual observed pollen concentrations at the aerobiological stations. In the source delineation studies for Finland (Paper IV) and the Moscow region (Paper V), footprint computations were performed that assumed passive Lagrangian air parcels, i.e., we had computed from where the air came into the pollen traps. On the other hand, more advanced computations were performed by Veriankatė et al. (2010), whereby pollen grains were assumed to behave as PM10 particles and both the Eulerian and Lagrangian dispersion schemes were applied.

In the SILAM forward pollen studies (Papers II and III; Siljamo et al. 2008), the source term includes the birch habitat map, the start of flowering, the duration and intensity of pollen release, and their vertical and horizontal distribution. The map of European birch forests presented in Section 3.1 was applied in our first attempts to model pollen LRT (Paper IV, Figure 3.1) with pollen grains assumed to be passive air parcels without removal processes. The start of flowering was based on climatological averages from Rötzer and Chmielewski (2001), and the length and intensity of pollination were fixed.

However, a more advanced pollen prediction system was introduced in Papers II and III, whereby the European birch map is the same as in early simulations except for some small additions (Figure 6.3, Paper III); however, the starting time of flowering was computed using accumulated temperature sums (Section 5.2, Papers II and III), and it treats pollen release as weather-dependent (Section 5.3, Paper II).

4 SOURCE AREAS OF LONG-RANGE TRANSPORTED POLLEN

Pollen footprint studies have been performed not only from an academic point of view, but also as a tool to support pollen predictions, in order to understand the conditions under which pollen LRT episodes can take place. Pollen LRT cases are fairly common in Northern Europe, as such events occurred, on average, every second year in the 1980s in Finland (Hjelmroos and Franzén 1994). Skjøth et al. (2007) found that there were significant pre-seasonal birch pollen episodes almost every year from 2000–2006 in Copenhagen.

Sometimes, LRTed pollen concentrations can be quite high. In 1989, for instance, LRTed birch pollen represented about 50% of the total birch pollen in Finland. Its source was eastern Central Europe (Hjelmroos and Franzén 1994). In 1999, this proportion was even higher, with almost all observed birch pollen in Finland originating from Russia (Figure 4.1 and Ranta et al. 2006). Footprint studies are also useful for understanding the differences between pollen counts and allergen content in the air (Buters et al. 2012).

Identifying sources of birch pollen has been the subject of several back-trajectory experiments. Hjelmroos (1991) studied birch pollen episodes in Finland and Sweden during the spring of 1989 that were traced back to source areas in South-Western Russia, the Baltic countries, and Poland, which are identical to those found in Paper IV. Hjelmroos (1991) also estimated that travelling time could be 9–20 hours, or even 50 hours, in some cases.

Skjøth et al. (2008a; 2009) studied elevated birch pollen counts in Copenhagen and London using back-trajectory analyses. Both studies argued that park trees contributed greatly to enhanced pollen concentrations from sources located outside the regions. In Denmark, the most important sources for such cases were Eastern Europe and Scandinavia (Mahura et al. 2007), where birch is a common tree, and Germany (Skjøth et al. 2008a), which is just south of Denmark.

Other backward pollen studies addressed ragweed pollen in Poland (Stach et al. 2007), grass pollen in the UK (Smith et al. 2008), *Altenaria* spores in Denmark (Skjøth et al. 2012), and oak pollen in Spain (Hernandez-Ceballos et al. 2011). In all these cases, pollen seemed to be both regional and LRT.

Sources of exotic pollen, i.e., pollen that cannot be local, have attracted the attention of scientists. Hjelmroos and Franzén (1994) made several trajectory analyses for 1987, 1991, and 1992, when strong southerly air circulation brought soil particles and exotic pollen grains from Southern Europe/Northern Africa to Fennoscandia. Franzén et al. (1994) estimated that dust and pollen grains had been transported over 7,000 km in 1991 during the so-called “yellow snow” event. They assumed that these kinds of LRT cases can be potentially important sources of error whenever interpreting paleopalynological pollen diagrams.

Pollen transport over several hundreds of kilometres was also estimated as marihuana pollen has been observed in Spain (Cabezudo et al. 1997), exotic pollen in Greenland (Rousseau et al. 2005), and ragweed pollen in Finland (Ranta et al. 2011).

We describe here some case studies of potential birch pollen LRT episodes for the years 1999 and 2004 (Papers IV and V; Ranta et al. 2006; Siljamo et al. 2007; Veriankaitė et al. 2010). Since it is not possible to find clear, systematic behaviours in pollen LRT episodes, we try to illustrate the main characteristics of pollen LRT cases, what challenges can be met in tracing back LRTed pollen source areas, and how pollen observations in the different locations may be linked to each other. In contrast to the examples above, the cases were not analysed using the trajectory analyses; rather, footprints were computed using an inverse dispersion approach (Sofiev et al. 2006). The differences between trajectory computations and inverse dispersion problems have been presented by Veriankaitė et al. (2010).

Our case studies investigate the source areas of birch pollen LRT episodes observed in North-Eastern Europe in early spring before the start of local flowering. Normally, LRTed pollen is observed in North-Eastern Europe after 1-2 weeks at the earliest and, rarely, up to 1 month, before local flowering. When pollen is observed only a few days before the start of local flowering, it is difficult to say whether it is an early onset of flowering nearby or true long-range transport. Moreover, mere scrutinising of observed pollen time series does not generally help to conclude whether its source is local or of LRT origin. For instance, in Figure 4.1, LRTed pollen peaks in Turku are substantially higher than local pollen peaks. Phenological observations have an important role when attempting to distinguish between the LRT cases and local pollination; still, because of the wide variability of phenological events (Paper I), they do not always give clear answers.

Finland and Moscow, 1999

Figure 4.1 shows an example of a significant and exceptionally high LRT episode in 1999 in Finland (Ranta et al. 2006; Paper V). The local flowering onset was late, due to a cold spring in Finland with exceptionally poor local flowering, but spring was characterized by a very abundant LRT episode, where LRTed pollen grains were observed throughout the country. At that time, LRTed pollen was observed as early as April 18–22 (the first two solid line peaks in Figure 4.1), when flowering in Southern Finland did not start until several weeks later on May 4, and for more than a month later, on May 20, in Northern Finland. The highest LRTed pollen concentrations reached 2,000–3,000 grains/m³.

At the same time as the LRT episode on April 18–22 in Finland, pollen concentrations in Moscow also increased several days before the start of local flowering (C1 in Figure 4.1). In this case, LRTed pollen grains were carried from the southeast.

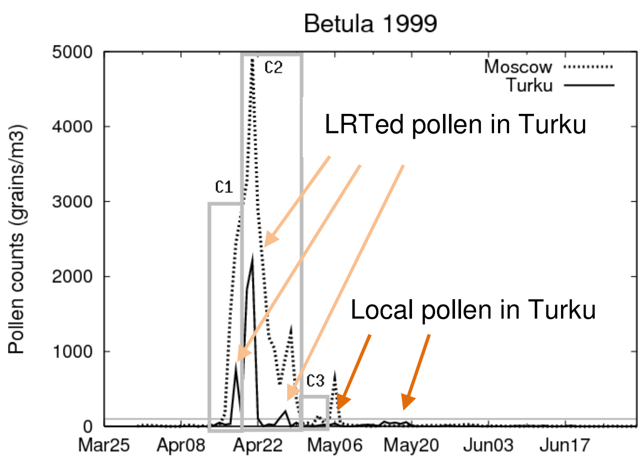


Figure 4.1 *Observed pollen counts in Moscow and Turku in 1999 (Paper V). The grey boxes indicate the case studies in Moscow presented in Paper V.*

During this spring of 1999, a high-pressure system was over Russia, while Sweden and Eastern Europe were within a low-pressure area, thus forming a saddle area over the Baltic countries and Poland. The saddle area made the flow unstable. As in other cases when a strong pollen LRT was observed in Finland (Sofiev et al. 2011), the source areas are located in Russia (Figure 4.2 a). When the Baltic branch of the saddle surface started to dominate, pollen concentrations decreased on April 19 (Figure 4.2 b); however, they rose again when the flow turned back from Russia (Figure 4.2 c, d).

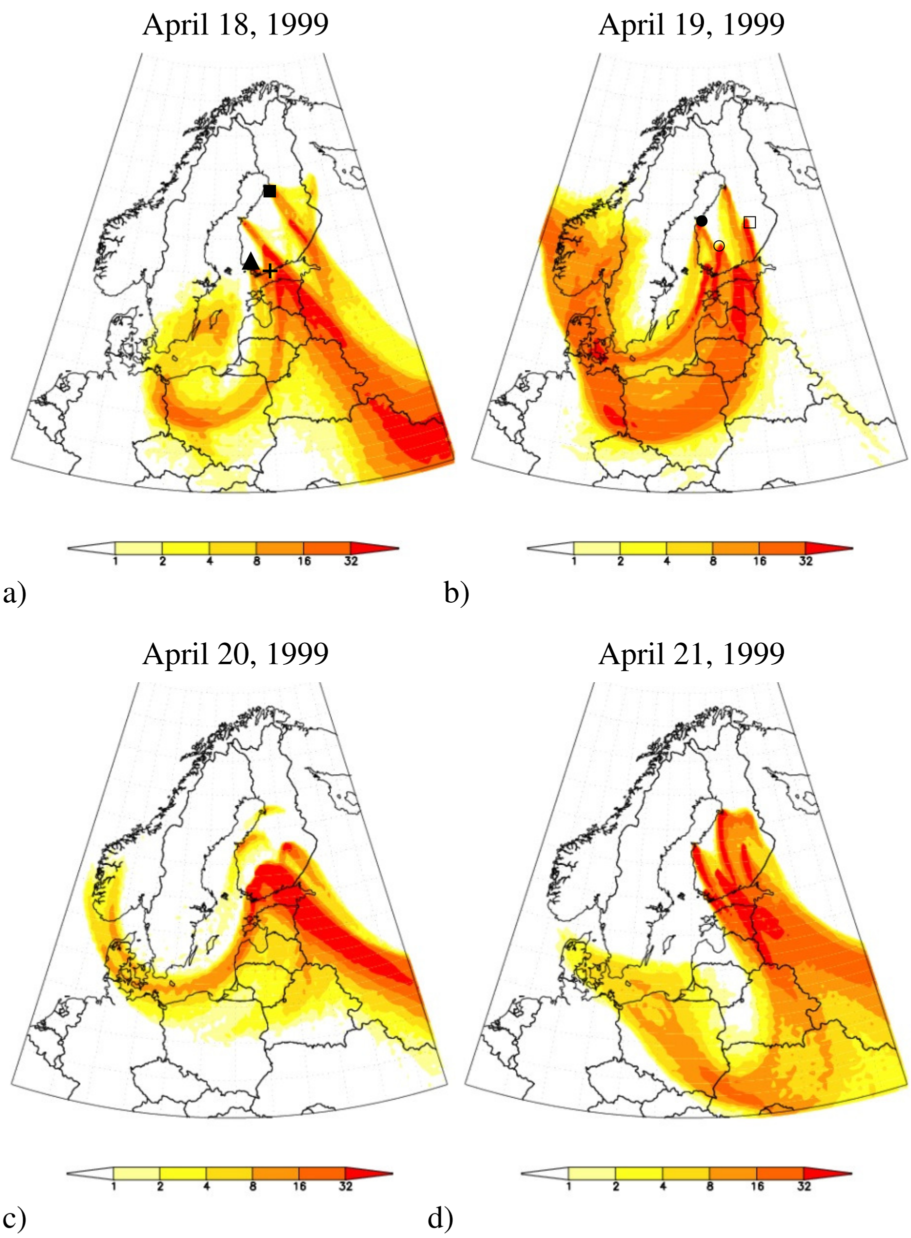


Figure 4.2 *Potential source areas of LRTed birch pollen observed at 5 stations in Finland (Turku (▲), Helsinki (+), Kangasala (○), Kuopio (□), Vaasa (●), and Oulu (■)). Footprint simulations 2 days backward when pollen was observed a) on April 18; b) on April 19; c) on April 20; and d) on April 21, 1999. The colour scale reflects the probability that an area serves as a pollen source. The white areas cannot be sources, and yellow areas have a low probability, while orange/red areas have high probability (Siljamo et al. 2006).*

Moscow, Finland, and Lithuania 2004

A fairly typical LRT episode was observed in 2004 in Moscow (Paper V). A very cold air mass was situated east of Moscow, while Western Europe enjoyed warm weather. Pollen LRT in Turku was observed before Moscow that spring, and pollination also started earlier in Turku than in the Moscow region (Figure 4.3). At the same time in Moscow, birch pollen concentrations increased on April 20–22 (to about 100 grains/m³) (box in Figure 4.3) when the westerly winds started. Because of the cold air, the actual pollination did not start until several weeks later, between May 4–7, and the observed pollen in Moscow came from the southwest and the west, i.e., from Ukraine and Belarus (Figure 4.4).

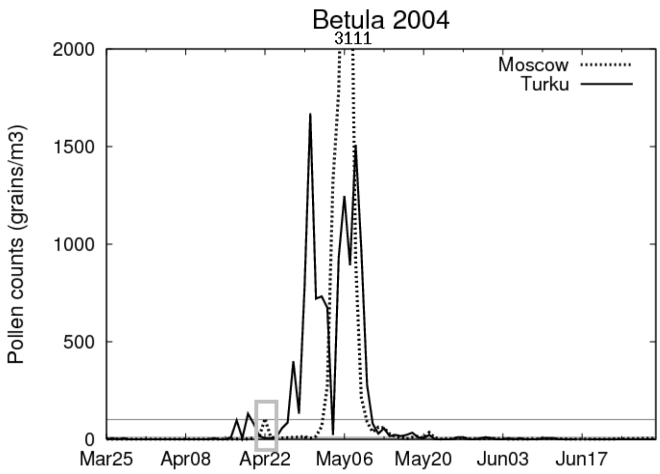


Figure 4.3 *Pollen counts in Moscow and Turku in 2004. The grey box indicates the Moscow LRT case. (Paper V)*

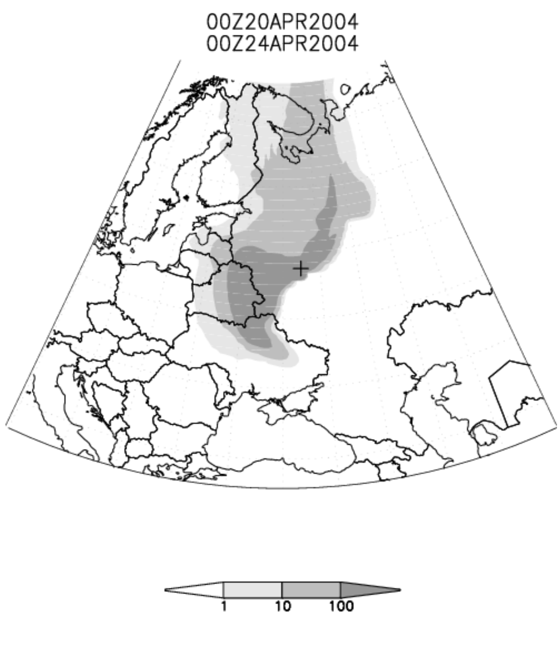
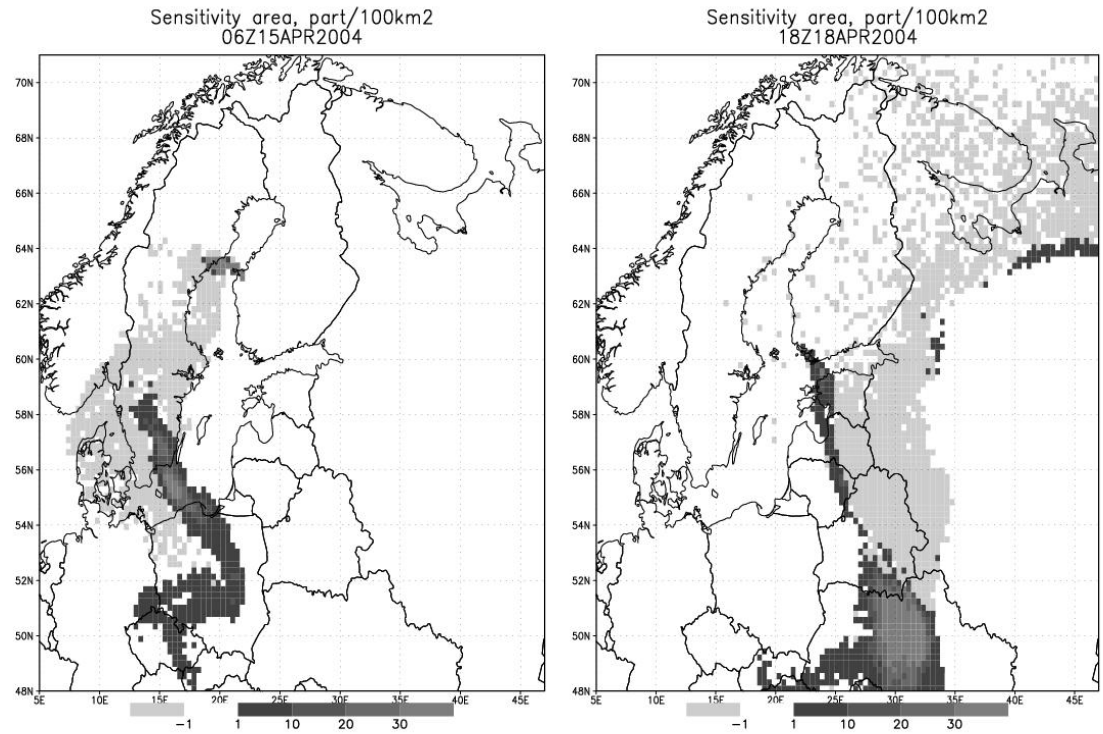


Figure 4.4 *Potential source area of LRTed pollen observed in Moscow. Footprint simulations 4 days backward when pollen was observed on April 20, 2004. The darker the area, the higher the probability that the area would serve as a source (Paper V).*

Meanwhile, in Finland, two LRT episodes also occurred before local flowering (Paper V; Siljamo et al. 2007). The first observations of birch pollen were on April 15–17 and again on April 19–22, just before LRTed pollen was observed in Moscow (Figure 4.3). The first pollen peak in Finland seems to have originated from Poland and possibly southern Sweden (Figure 4.5a), whereas the second peak originated from Belarus and Ukraine (Figure 4.5b), i.e., the same source areas as Moscow (Figure 4.4).

In addition, two LRT cases were also observed in Lithuania during the spring of 2004. The first was observed even before the middle of April, and the other was at the same time as in Finland and Moscow on April 18–22, when the source region was the same: Ukraine and Belarus (Veriankaitė et al. 2010).

However, determining the sources seemed to be an overwhelming task for the dispersion models in the first early LRT episode in Lithuania on April 12–14. Birch pollen was most likely transported from the west (Figure 4.6). Both the SILAM and the HYSPLIT models provided a strong hint that the pollen would have come from southern Sweden, like in the first case in Finland on April 15–17 (Figure 4.5a). However, Swedish pollen observations for these days do not support such a conclusion (Figure 4.6). Although the distribution patterns produced by the dispersion models only brushed past Poland, it is still possible that pollen could have come from this area, as the observed birch pollen on April 17 in Finland did (Figure 4.5a).



a) b)

Figure 4.5 *Potential source area of birch pollen observed at 5 stations in Finland (Turku, Helsinki, Vaasa, Oulu, and Kangasala) a) on April 15–17, 2004 (instantaneous view on April 15, at 6 UTC) and b) on April 19–21, 2004 (instantaneous view on April 18, at 18 UTC). The simulations are 0–2 days backward. Light grey shading indicates areas that should not supply pollen grains, while the dark grey areas probably act as sources (Siljamo et al. 2007).*

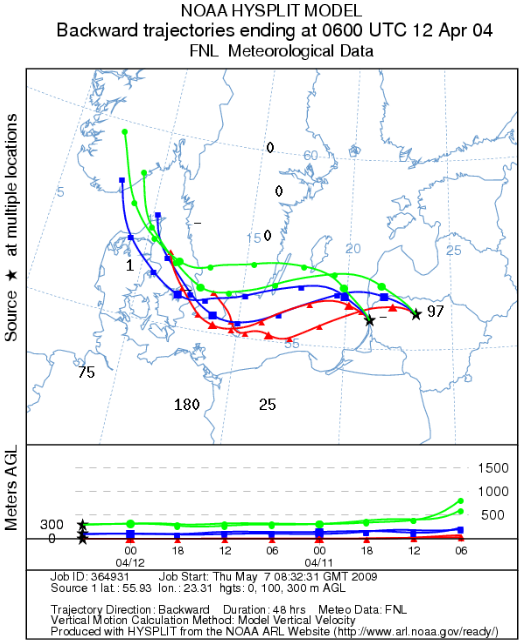


Figure 4.6 *Potential source of pollen observations on April 12, 2004 at Siauliai (97 pollen grains/m³ observed) and Klaipėda (no observed pollen) in Lithuania, using the HYSPLIT model with trajectories at various altitudes (shown in the below panel; red is the surface trajectory). Numbers on the map indicate Betula pollen counts on April 10 or April 11, 2004. (Pollen observations are from the EAN database).*

General features of LRTed pollen in North-Eastern Europe

Although we have not performed any systematic LRTed pollen footprint studies for Finland like Mahura et al. (2007) did for Denmark, the existing pollen LRT case studies in Finland, Moscow, and Lithuania in 1994–2007 (Papers IV and V; Ranta et al. 2006; Siljamo et al. 2007; Veriankaitė et al. 2010; Ranta et al. 2011; Sofiev et al. 2011) showed that pollen LRT often occurred when a high-pressure area lies over Russia, which induces south-easterly winds that bring pollen to Finland.

Despite the prevailing south-westerly winds in Finland, the source of observed LRTed pollen grains in Finland is rarely from Sweden (though it can happen sometimes as in 2003; see Paper IV), in spite of an earlier spring, with birch as a common tree there. This may be due to the fact that the cold Baltic Sea creates an overlying stable boundary layer with no sufficient upward motions. When abundant pollen LRT is observed in Finland, it comes mainly from the south and southeast (Paper IV; Ranta et al, 2006; Siljamo et al. 2007; Sofiev et al. 2011; Ranta et al. 2011).

LRT episodes also occur frequently in Moscow, which possesses a southern contribution, in addition to a western one (Paper V). Lithuanian cases are much more complicated, although even there, the most important LRTed pollen comes from the south and southeast. In some cases, it is almost impossible to know the pollen source area with certainty (Veriankaitė et al. 2010). One natural reason is the inherent uncertainties embedded in NWP and atmospheric dispersion models. Additionally, pollen observations and phenological networks can be too sparse. However, it is also possible that pollen grains are transported higher in the atmosphere and, thus, pollen traps along the way cannot detect them.

5 EMISSION MODELLING

Determining the emission of pollen grains (i.e., where, when, and how much pollen grains are released into the atmosphere) includes determining source areas, timing of flowering, and pollen release. In case of birch, the source areas remain fairly constant over time, but the timing and amount of released pollen are dependent on many (weather-related) factors. Modelling these processes aims to describe when and how pollen grains are released into the atmosphere via mathematical formulations.

Birch pollen emissions in the SILAM model are represented with both a phenological model that forecasts the starting time of flowering in Europe (Section 5.2, Papers II and III) and a pollen release model (Section 5.3, Paper II).

5.1 PHENOLOGICAL MODELS

The effect of temperature on phenological events is not a new idea. Réaumur (1735) suggested that temperature affects the timing of phenological events and, thus, the time differences between phenological events and between places can be explained by differences in air temperature. The temperature sum still plays a key role in modelling bud bursts in boreal and temperate trees.

Despite its long history, the key problem in phenological modelling is still that the physiological processes that control plant phenology are largely unknown (Schaber 2002; Linkosalo et al. 2006). Therefore, instead of going very deeply into the physiological processes, phenological models usually only take into account the effect of weather on phenological events.

Climatological date of phenological phases

Rötzer and Chmielewski (2001) computed climatological estimates of specific phenophases for various species according to longitude, latitude, and altitude. In Europe, the growing season begins in the south-western corner and proceeds to move north-east. As altitude increases, the growing season is delayed by about 3 days/100 m. The transition from west to east delays the phenomenon by about 0.5 day/100 km and from south to north by about 2.3 days/100 km.

Since the timing of phenological events varies from year to year and time differences between adjacent areas are large (e.g., Paper I), assuming fixed dates, despite its simplicity, is not suitable for numerical pollen concentration simulations (Paper IV). Since the start of birch flowering varies at a given place by roughly ± 2 weeks, but flowering itself last two weeks, on average (Sarvas 1955), pollen forecasts based on fixed dates would, in practice, be of no use.

Thermal Time–type models

The simplest phenological model is the classical thermal time–type linear temperature sum model (e.g., Robertson 1968) based on an integral of the temperature T

(5.1) $$H(t)=\int_{t_0}^{t}\left(T(t)-T_{crit}\right)dt, \text{ when } T>T_{crit} ,$$

where H is the temperature sum, t is time, t_0 is the moment at which the temperature sum accumulation is started, and T_{crit} is the critical threshold temperature above which the temperature sum starts cumulating. The parameters to be optimised are the starting date (t_0) for the temperature sum accumulation, the threshold temperature (T_{crit}), and the temperature sum (H). Often, the temperature sum calculation is started on the first of January or near the spring equinox, e.g., at the beginning of March (Linkosalo et al. 2006, 2008). The temperature forcing is not necessarily a linear function of temperature, as in Eq. 5.1, but different functions, e.g., sigmoidals, can describe the amount of forcing (Sarvas 1972; Hänninen 1990; Chuine 1999, 2003; Linkosalo et al. 2008).

Parallel and sequential models

It has been observed that boreal and temperate trees do not react to temperature forcing until they have received a sufficient amount of chilling (Hänninen 1986; Häkkinen et al., 1998; Chuine et al. 2003). The more chilling that a plant gets, the less temperature forcing is needed for bud burst (e.g., Chuine 1999; Junttila and Hänninen, 2012).

Phenological models become slightly more complex when chilling days are also included (Hänninen 1990; Kramer 1994). So-called sequential or parallel models are examples of such models. They take chilling into account in slightly different ways. Sequential models start the temperature accumulation when a sufficient amount of chilling is reached. In parallel models, both chilling and temperature sum accumulation take place at the same time, i.e., a positive temperature forcing is building, even if the sufficient level of chilling has not yet been reached. In addition to the critical minimum temperature, the temperature forcing function is often defined using optimum and maximum temperature, in which case, for example, forcing is a triangular or sigmoidal function (e.g., Sarvas 1972; Hänninen 1990; Chuine et al. 2003; Schaber and Badeck 2003).

Flexible models

Chuine (2000) has developed a so-called unified model, in which the thermal time, sequential, and parallel models are special cases. She has simplified the unified model into two models: the UniChill and UniForc models. The UniChill model, as the name suggests, takes chilling into account, and the temperature forcing only actualises when a sufficient chilling level is reached. The model includes seven optimized parameters. In the UniForc model, chilling is not considered at all. The temperature accumulation begins, as in thermal time–models, at a fixed date. This way, the number of optimized parameters can be further reduced to four. The optimized values of the parameters define the shape of the forcing function.

Signal theory

When the above models only take air temperature into account (the so-called autonomous development theory), according to signal theory, an environmental signal can trigger the phenological stage. In signal theory models, the most commonly used indicator is the length of the day or night (Hänninen 1986).

Schaber and Badeck (2003) developed a so-called promoter–inhibitor model, whereby one calculates promoting (ΔP) and inhibitor (ΔI) factors for phenological events. These factors are affected by temperature and the length of the day. The calculation starts in autumn on the observed date of leaf colouring, with $I(t_0) = 1$ and $P(t_0) = 0$. Bud burst happens when $P(t) = 1$. In the case of birch, the key factor influencing the inhibitor I is the chilling temperature. For the promoter factor P, in addition to air temperature, the length of the night is also important.

Assessment

Number of factors support the simplest temperature sum model for numerical pollen simulations. Chuine et al. (1999) found thermal time –type models to be at least as accurate, and sometimes even more accurate, than parallel and sequential models for temperate trees bud burst. Linkosalo et al. (2006, 2008) also showed that the linear temperature sum model is at least as good in boreal climates, and often better than, more complex phenological models. Since the physiological and biochemical processes behind phenological events are still relatively unknown, using more comprehensive phenological models increases the risk of over-parameterization, because models are able to adapt to noise present in the data (Linkosalo et al. 2008).

In addition, the phenological model of a numerical pollen application should match and be kept as simple as possible in the first model versions. Model developments and corrections, both technical and theoretical, would be easier this way. Also, from the practical, operational point of view, it is better if the model is not too complicated or heavy, and that chilling or temperature sum accumulation times do not grow too long. For example, with a six-month accumulation time, even the slightest bias in the NWP model will yield large departures in the results.

5.2 TEMPERATURE SUM MAPPING IN SILAM

The estimation of the temperature sum parameters is presented in Papers II and III. The temperature sum for the start of flowering was calculated for Europe using the phenological dataset presented in Section 3.2. The meteorological input was the ECMWF's ERA-40 dataset (Uppala et al. 2005, Section 3.4). Because only leaf unfolding is observed in all countries, which is included in the collected database and with time-series that were long enough, it was used to describe the beginning of flowering. However, in nature, birch starts to pollinate a couple of days before the onset of leaves (Linkosalo 1999).

Pollen observations were also used to time flowering (Paper III). Pollen observations came from the European Aeroallergen Network (EAN). Local bloom was assumed to begin when 2.5% of the annual total pollen count was reached (Goldberg et al. 1988). This value has been found to work well in Central Europe, but not for Northern Europe, where this percentage is too low (Ranta et al. 2006).

The best estimate for the temperature sum was tried using the gradient minimization method. Hereby, we need to find the most appropriate day to start the temperature sum accumulation, as well as the best critical temperature.

In the one-parameter fitting, only the temperature-sum threshold for flowering H_{fs} varied, while the starting date of the temperature-sum accumulation D_s and the temperature cut-off limit T_{crit} were fixed. In the two-parameter fitting, the starting date of temperature-sum accumulation was fixed, while the critical cut-off temperature and the temperature-sum varied. In the three-parameter fitting, all three variables varied.

To compute the temperature sum H, we used the discrete version of its definition in Eq. 5.1:

(5.2) $$H(D)=\sum_{d=D_s}^{D}(\overline{T(d)}-T_{crit})\text{, when }\overline{T(d)}>T_{crit}\,.$$

Here, D is day, the bar denotes the daily average constructed from the 6-hour ERA-40 values, and D_s is the starting date of the temperature sum H integration.

As climate conditions vary considerably across Europe, one cannot assume that the same temperature sum value will work everywhere. Therefore, we determined about 30 "reference points" around which the temperature sum was optimized. The radius of one circle was approximately 600 km, and the circles were partly overlapping.

In the model, the starting date of the flowering, $D_{fs}^{mdl}(s)$, was then defined for a specific station s as the first day when $H(D,s)\geq H_{fs}$. The criterion for the fitting was to minimise a cost function J_{fs}, based on the RMS of the model predictions, $D_{fs}^{mdl}(s)$, versus the observed values, $D_{fs}^{obs}(s)$:

(5.3) $$J_{fs}(H_{fs},D_s,T_{c-o},r)=\frac{1}{N_r}\sum_{s=1}^{N_r}(D_{fs}^{mdl}(s)-D_{fs}^{obs}(s))^2\rightarrow\min_{H_{fs},D_s,T_{c-o}}\,.$$

Here, N_r is the number of stations in the sub-region r, and J_{fs} is the sub-regional cost function.

It turned out that the cost function values were the same or higher when optimizing 2 or 3 parameters, compared to optimizing only the temperature sum. Practical applications are also simplified if the temperature sum accumulation starts everywhere at the same time. Since the final temperature sum map combines information from several partly overlapping reference points, it would be quite complex to also ensure the accuracy of the thresholds over different regions.

Day number 60 (usually March 1) was chosen as the starting date of the temperature sum calculations. Based on the experience with 2- and 3-parameter fittings, this date is somewhat late for the British Isles and Spain but somewhat too early for Northern Europe, although it works as a compromise. Similarly, the temperature sum threshold value of 3.5 °C is a compromise. Again, the value is too low for Southern Europe and marine climates. As birch is a common tree, particularly in Northern Europe, the suitability of the threshold was focused on these areas.

Figure 5.1 shows the cost function J_{fs} as days when the leaf unfolding observations are used. The residual is small in Northern Europe and under continental climates, but large in southern and/or marine climates, just as the observations suggested (Figure 3.2).

The temperature sums range from about 50 DD (degree days) in Northern Europe to typically 80–90 DD in Central Europe, up to 130 DD in the British Isles, when leaf unfolding (LU) data are used (Figure 5.2a). When we use the date derived from the pollen data, the temperature sum values range from 6 DD to 108 DD (Figure 5.2b), yielding Northern European values that are typically less than 20 DD, which is unrealistically low. This is due to significant pollen LRT before the start of local flowering (Ranta et al. 2006). Thus, the 2.5% assumption for the start of the local flowering is not suitable for Northern Europe.

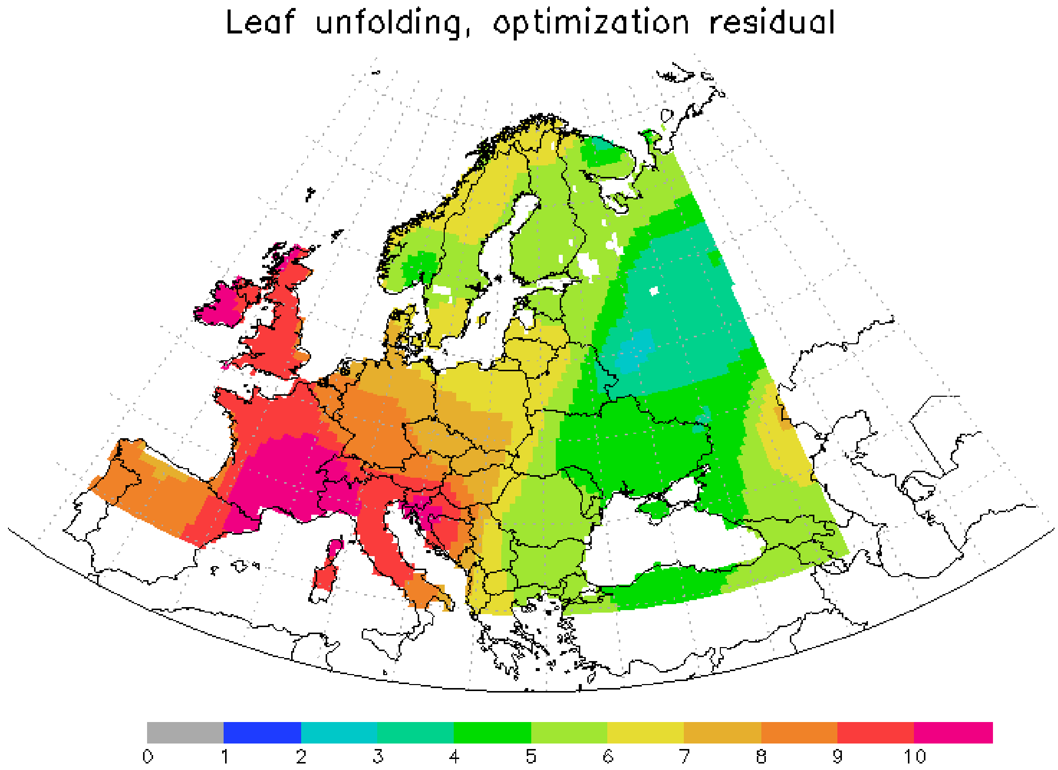
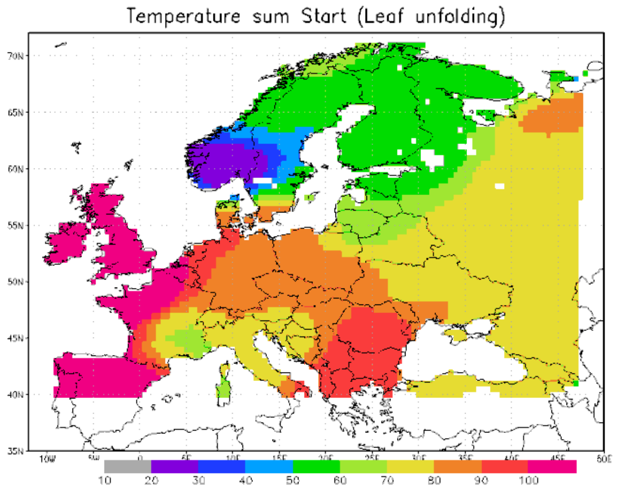


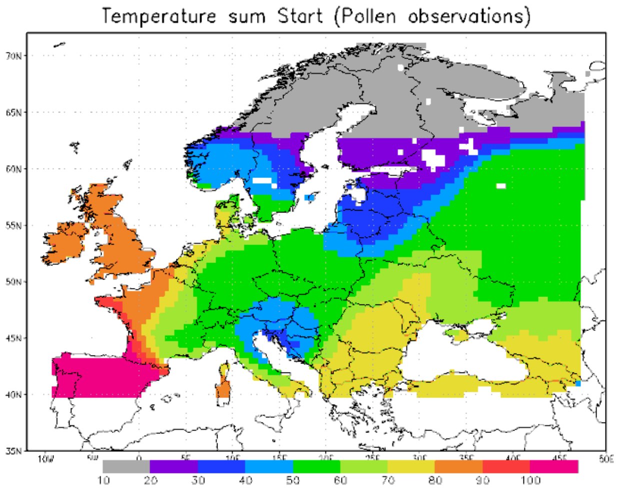
Figure 5.1 *Cost function J_{fs} (in days) over Europe, when leaf unfolding observations were used (Paper II).*

The hypothesis that pollen observations could describe the beginning of flowering better than leaf unfolding observations was tested, since birch leave outbreaks occur after birch pollination starts. For this purpose, a so-called combination threshold map was compiled. It was derived using leaf unfolding observations in Northern Europe and mountainous areas, while elsewhere, we used pollen observations, if available. This generated a map where the temperature sum values for birch flowering were 50–60 DD over a wide area of Northern Europe, Russia, and Central Europe (Figure 5.2c). On the basis of SILAM pollen simulations, this hypothesis was not proven to be correct, although the differences were not large (Section 6.2, Paper III).

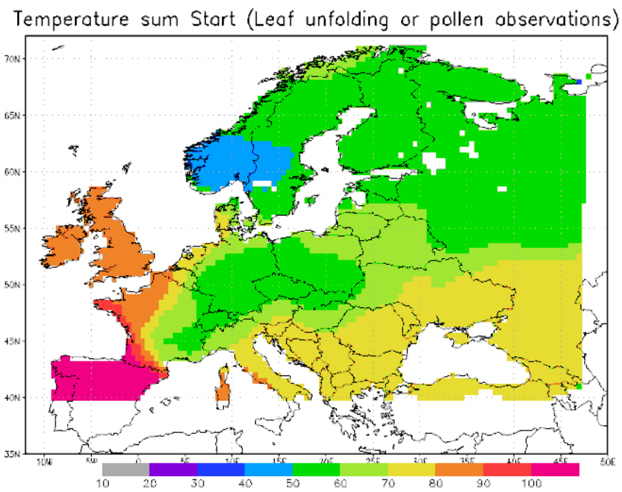
The LU-based threshold map was analysed using the classical work by Linsser (1867). According to Linsser's Law, for any heat-driven phenological phenomenon, a heat-sum threshold is a constant fraction of the overall accumulated Effective Temperature Sum (ETS) over the whole growing period. In other words, the map of the heat sum threshold should be proportional to the ETS map, which can be easily computed from meteorological data over the period of active vegetation. The ratio of H_{fs} to ETS computed for 2006 is indeed nearly constant over the European continent. Exceptions include the mountainous areas and northern Lapland, for which the phenological information was almost non-existent and the applicability of both Linsser's law and our fitting was questionable (Paper II).



a)



b)



c)

Figure 5.2 *Temperature sum maps as degree-days (DD) based on: a) leaf unfolding (LU), b) pollen observations, and c) combination maps (Paper III)*

5.3 THE POLLEN RELEASE MODEL IN SILAM

Pollen release in the SILAM model is presented in Paper II. The parameterization of flowering in the SILAM emission model follows the principle of two thresholds for the temperature sum (Linkosalo et al. 2010), which assumes that the timing of birch flowering is mostly driven by the accumulated ambient temperature during a certain time period.

According to Linkosalo et al. (2010), the cumulative fraction R of pollen released from the beginning of a year until time t is piecewise linear and proportional to the temperature sum H during the main flowering season.

$$R(t) = \begin{cases} 0, & H(t) < H_{fs} \quad (\textit{before the season}) \\ \dfrac{H(t) - H_{fs}}{H_{fe} - H_{fs}}, & H_{fs} < H(t) < H_{fe} \quad (\textit{ongoing season}) \\ 1, & H(t) > H_{fe} \quad (\textit{season over}) \end{cases} \tag{5.4}$$

The temperature sum thresholds for the start (H_{fs}) and end of the season (H_{fe}), as well as the form of the function $H(t)$, have to be identified from observational data (Section 5.2).

The output of the emission module is described as a release flux of pollen grains $E(t, i, j)$: the number of grains emitted from 1 m^2 of birch forest within 1 second in a given model grid cell (i, j). For dispersion computations, the model emission flux $E_{\mathrm{mdl}}(t, i, j)$ is obtained from $E(t, i, j)$ by multiplying it with the fraction of birch $\varphi(i, j)$ and the grid cell area $S(i, j)$:

$$E_{mdl}(t, i, j) = E(t, i, j)\varphi(i, j)S(i, j)\,. \tag{5.5}$$

The term $E(t, i, j)$ has to be further decomposed using the double-threshold model of Eq. 5.4:

$$E(t, i, j) = \frac{dR}{dt} N_{total}\; p(t, i, j)\, F(meteo)\,. \tag{5.6}$$

Here, N_{total} is the total number of pollen grains released from 1 m^2 of birch forest during the whole season, $p(t, i, ,j)$ is the probability of a tree in the given grid cell to flower at the specific time, and F(meteo) is the flux correction, which depends on meteorological factors.

As shown in Paper I (Section 3.2), the uncertainties in the season timing are large. As a result, any deterministic model of the flowering season would be inaccurate, due to the large scatter around the stable mean heat sum threshold. Indeed, transport conditions are dictated by the meteorological situation. Therefore, a shift in pollen release would lead to incorrect release parameters and to different dispersion patterns of emitted pollen. The solution implemented in SILAM describes the flowering in probabilistic terms, which extend the flowering period: it takes longer to release the prescribed N_{total} pollen if some trees are not flowering during part of the season.

The end of the season is determined based on the "open pocket" principle; in other words, the emission continues until $N = N_{\mathrm{total}}$. The temperature sum difference $\Delta H = H_{\mathrm{fe}}\text{-}H_{\mathrm{fs}}$ only plays a role in the relative pollen release rate *dR/dt* in Eq. 5.6. The term H_{fe} is only needed to determine ΔH.

To obtain *dR/dt*, we used the linear temperature sum formulation presented in Eq. 5.4. Then, the relative release rate becomes a piecewise linear function of temperature:

$$(5.7)\qquad \frac{dR(t)}{dt} = \begin{cases} 0, & H(t) < H_{fs} \\ \dfrac{dH(t)/dt}{H_{fe} - H_{fs}} = \dfrac{T(t) - T_{crit}}{\Delta H}, & H_{fs} < H(t);\, R(t) < 1;\, T(t) > T_{crit} \\ 0, & R(t) > 1 \end{cases} .$$

Eq. 5.7 requires three parameters: the temperature sum threshold H_{fs} for the start of flowering, the difference between the thresholds for the start and the end of pollen release $\Delta H = H_{\mathrm{fe}}\text{-}H_{\mathrm{fs}}$, and the critical temperature T_{crit}. In practice, this means that the warmer the weather is, the faster pollen is released.

Pollen is not released from catkins in moist and rainy weather, but the temperature sum may still be accumulating. Thus, the temperature sum, which describes the end of pollination, has no use in this application. The temperature sum difference used in Eq. 5.7 is empirically determined to be constant (50 DD) for the whole of Europe in the SILAM pollen simulations presented in this thesis.

Pollen concentrations and weather interactions in the SILAM model

In general, there is no pollen release if the weather is cool and cloudy and the relative humidity is high. On the contrary, pollen grains are released from catkins when the weather is bright and warm and relative humidity is low. In the latter case, turbulent conditions and thermally generated eddies contribute to the release and to pollen dispersion. Relatively low average wind speeds, combined with strong gusts, are particularly effective. This kind of weather is typical of convective conditions. Jackson and Lyford (1999) computed that greater vertical diffusion near the source increases pollen ascents in the atmosphere, and thus leads to a wider dispersion. For example, a small pollen grain in neutral conditions is transported only 250 m (20% of the original amount), but 4 km in unstable conditions.

According to Wright (1952), wind speed and direction are important for pollen dispersion, since downstream dispersion is the most effective factor. On the other hand, Puc (2012) found maximum temperature and humidity to be the most important weather parameters when using an artificial neural network model.

Mahura et al. (2009) developed a parameterization of the birch pollen diurnal cycle. Helbig et al. (2004) developed a very detailed pollen emission flux expression. Their model includes friction velocity, leaf area index, temperature, humidity, wind speed, and several scaling factors.

In the SILAM model, the emission term is considerably simpler. The term *F*(meteo) in Eq. 5.6 only includes four weather parameters that affect pollen release. Wind speed and convection promote pollen release, while rain and high relative humidity decrease or even stop it. High temperature effects via the relative pollen release rate dR/dt in Eq. 5.6 promote pollen release. Both in nature and in NWP models, all factors influence each other and are thus not independent of each other.

Precipitation- and humidity-related corrections are derived from known "prohibiting" thresholds that totally suppress pollen release. Until these thresholds are reached, these variables do not affect the release (neither do they promote it). Near the threshold, the piecewise linearly decreasing transition function is as follows:

$$(5.8) \qquad f_{thr}(x, x_{low}, x_{high}) = \begin{bmatrix} 1, & x \le x_{low} \\ \dfrac{x_{high} - x}{x_{high} - x_{low}}, & x_{low} < x < x_{high} \\ 0, & x \ge x_{high} \end{bmatrix},$$

where x represents rain or relative humidity. Rain stops pollen release; however, rain prediction in NWP models and how it should affect pollen release is not quite unequivocal. Since rainfall from rain showers are distributed throughout a grid cell in NWP models, some of the model birch trees within a grid cell may release pollen into the atmosphere. Thus, in model simulations, a weak rain event cannot completely stop pollen release. The lower and upper thresholds of precipitation are P_{low} = 0 and P_{high} = 0.5 mm/h. Yet, even without the rain, high relative humidity (RH_{high} = 80%) often stops pollen release. The pollen emission rate in the SILAM model is set to slow down as early as when the relative humidity RH_{low} exceeds 50%.

Figure 5.3 shows the separate dependency of observed and predicted birch pollen counts on meteorological parameters. When the observed and modelled pollen count are compared to each other, airborne pollen is virtually absent with rainy weather in both cases. Pollen does not occur in the air under moist weather (RH> 80%), as release is prevented from catkins. On the other hand, pollen has not been observed either under very dry weather conditions (RH <40%), because such cases are few. Both observations and model simulations behave almost similarly.

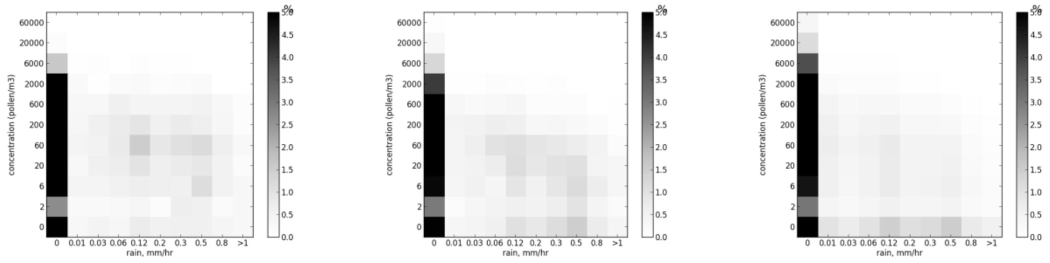
If pollen levels are assessed on an hourly basis, most of the cases concentrate in low pollen levels and high relative humidity (RH>70%). Rain is part of the explanation, but these situations may be explained by night cases, too. Thus, weather parameters control pollen emission, but external forcing is not required to control the diurnal variation.

Wind speed also has a significant modulating role in the SILAM pollen simulations through three required phenomena. In the case of low wind but developed thermal convection, turbulence alone is sufficient to kick-start the release by generating sub-grid convective winds. Stronger wind promotes the release by picking the pollen grains from open catkins. After reaching some critical level, further wind increases do not affect the release rate, which is then limited by the availability of ripe pollen grains in the catkins. These phenomena can be included in a single function, as follows:

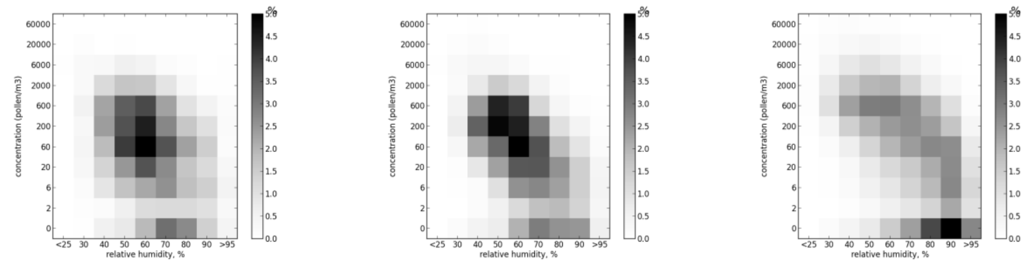
$$(5.9) \qquad f_{wind} = f_{stagnant} + f_{promote}\left[1 - \exp\left(-\frac{U + w^*}{U_{satur}}\right)\right].$$

Here, U is the wind speed, w^* the convective velocity scale, U_{satur} is the saturation wind speed, and ($f_{\text{stagnant}} + f_{\text{promote}}$) is the maximum benefit that wind can give to the release rate. In calm conditions, Eq. 5.9 suppresses the release by the f_{stagnant} factor.

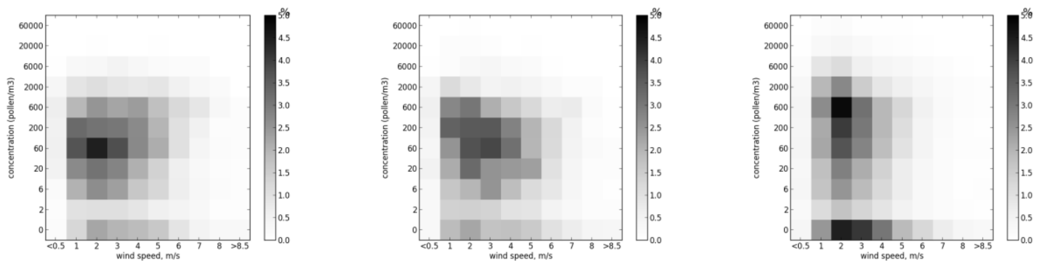
Rain (mm/h)



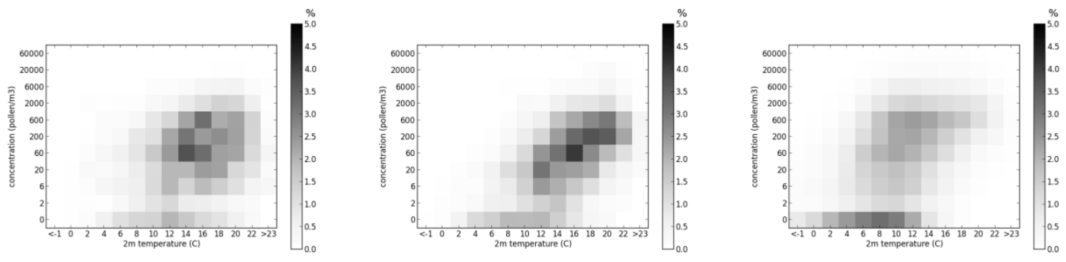
Relative humidity (%)



Wind speed (m/s)



2 m temperature (ºC)



Daily observed | Daily predicted pollen counts (grains/m³) | Hourly predicted

Figure 5.3 *Dependence of the daily observed (**left**), daily predicted (**middle**), and hourly predicted (**right**) birch pollen counts (grains/m³) on the meteorological forcing: Rain intensity (mm/h, **1st row**), relative humidity (%, **2nd row**), wind speed (m/s, **3rd row**), 2 m temperature (ºC, **4th row**). The grey scale depicts the fraction (%) of values falling into the corresponding range of values (revised from Paper II)*

In the current version of SILAM, U_{satur} = 5 m/s, $f_{stagnant}$ = 0.5, and $f_{promote}$ = 1, which implies no impact at wind speed ~1 m/s, since a typical value for w^* is 1–3 m/s in the daytime convective boundary layer. The model yields a three-fold stronger release in very strong winds, compared to calm conditions.

Wind speed is often stronger during rainy weather, but since there is no pollen release in such cases, the significance of wind speed remains unclear. Thus, one cannot clearly distinguish that the growth of wind speed clearly increases pollen counts, neither from observations nor from model simulations (Figure 5.3). Most of the highest pollen counts are observed during relatively weak wind speeds (2–3 m/s). This is particularly evident in the hourly values of model simulations with a clear peak detected at wind speeds of ~2 m/s. Such weak wind cases are often observed in spring in high pressure areas where the weather is sunny, relatively warm, and rainless. This result agrees well with those of Jackson and Lyford (1999).

If temperature is less than the critical value (i.e., 3.5 ºC) in the temperature sum, the model yields no pollen release. Otherwise, the warmer the weather is, the faster pollen is released from catkins (Eq. 5.7). High temperature increases pollen concentrations. This statement is more clearly supported by the model simulations than by the observations. As the birch trees pollinate in spring, few high temperatures are usually detected during the peak blooming days. Later in spring, the temperature rises, but flowering is already coming to an end.

6 MODEL APPLICATIONS AND EVALUATION

This section describes the operational SILAM pollen simulations at FMI (Section 6.1) and tries to answer whether the model is suitable for its purpose and whether its skill is adequate (Section 6.2). This is called model verification, or more broadly speaking, model evaluation. We have tried to find the indicators that best describe the model's suitability for pollen forecasting. The correct timing of flowering is a key part of a successful pollen prediction, and thus, bias and RMS error has been used to evaluate it. Instead, the exact number of pollen grains is less important, while pollen observations contain uncertainties. The correct order of magnitude for concentrations is more important; therefore, categorical statistics were selected to describe the goodness of the SILAM pollen concentration predictions.

6.1 SILAM SIMULATIONS OF FULL BIRCH POLLEN SEASONS AT FMI

Numerical pollen concentration forecasts for Europe have been produced by FMI since 2005. In 2007, we started birch pollen predictions based on temperature sums. In 2013, the SILAM pollen simulations include birch, as well as grass (Siljamo et al. 2010), olive (Galan et al. 2013) and ragweed (Bullock et al. 2012; Prank et al. 2013). The daily birch pollen forecasts start on March 1 and they continue on a daily basis until the end of June. The lead time of the forecasts is 5 days.

The structure of the simulation system is presented in Figure 2.1. The predictions are run using the Eulerian SILAM version with 15 min time steps and about a 20 km grid resolution. NWP input data comes from the ECMWF injected with 3-hour time steps. The birch source area is presented in Figure 6.3. The leaf unfolding–based linear temperature sum predicts the start of flowering (Figure 5.2a.), and the weather influences pollen release (Section 5.3).

Forecast results are available on the website http:\\silam.fmi.fi as an animation. A visualisation example of the SILAM pollen forecast on the website is shown in Figure 6.1. The visualisation includes predicted pollen concentrations over Europe, as well as accumulated temperature sum and the stage of flowering.

A special feature of SILAM birch pollen forecasts, compared to other numerical pollen simulations, is both the geographical and temporal coverage. SILAM predicts pollen concentrations throughout Europe and over the entire pollen season (not only for some cases) from early spring, with observed pollen LRT, to the start of flowering, and further until the end of the season. Furthermore, the operational capability of the SILAM pollen forecasting system is rather unique, with only MeteoSwiss having recently started daily pollen simulations with COSMO-ART.

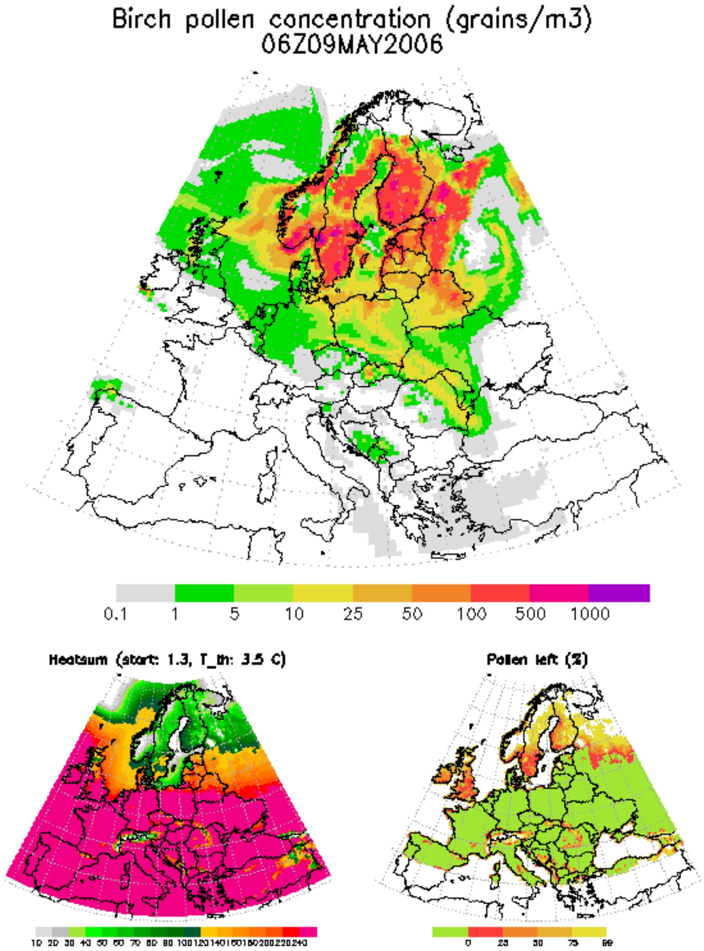


Figure 6.1 *An example of the SILAM pollen forecast on May 9, 2006. Upper panel: birch pollen concentration; bottom left: temperature sum; bottom right: stage of flowering.*

6.2 EVALUATION

The reliability of the SILAM pollen model was assessed during the pollen season of 2006 (Paper III). Birch flowering began in the south-western corner of Europe in March and proceeded towards the northeast. By the beginning of June, pollination was mostly over, except in Lapland. Spring of 2006 was characterized by strong pollen LRT episodes from Eastern Europe and western Russia that went through part of Central Europe and northwards up to Spitsbergen and Iceland (Sofiev et al. 2011). At the same time, wildfires in Russia caused poor air quality throughout Europe (Saarikoski et al. 2007; Stohl et al. 2007).

The model was evaluated further by testing two different NWP model inputs: those from ECMWF and from HIRLAM (Section 3.4). In addition, two different temperature sum maps were tested (Section 5.2). One temperature sum map is only based on phenological observations (Figure 5.2a), and the other one is based on both pollen and phenological observations (Figure 5.2c). A temperature sum map based solely on pollen observations was not used, since the temperature sums are unrealistically low for Northern Europe (Figure 5.2b).

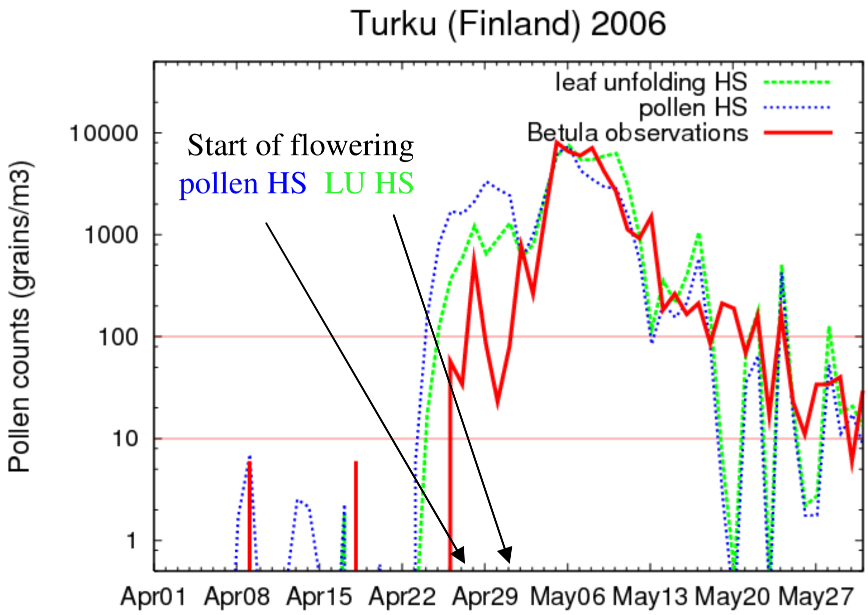


Figure 6.2 *Birch pollen observations (red) and SILAM forecasts during the spring of 2006 in Turku using only leaf unfolding (LU, green) and pollen observation (blue)–based temperature sum (HS) maps. (Pollen data: University of Turku, Aerobiology Unit)*

The comparison between observed and predicted birch pollen concentrations for the spring of 2006 in Turku, Finland is shown in Figure 6.2, where the pollen season is fairly well-predicted. The model predicted that the pollen season would start a couple of days too early and that it would be caused by an LRT event. The first peak in late April, which was a bit overestimated, was due to pollen LRT from Russia; still, the highest pollen concentrations are generally well-predicted. Flowering in the SILAM model starts either on May 1 (based on the LU-based temperature sum) or on April 28 (using only the pollen-based temperature sum). At the end of the season, the model did not show a monotonous decrease of concentrations, but, strangely, displayed several erratic minima.

Timing of birch flowering

The accuracy of the starting time for birch flowering was evaluated by comparing the dates when pollen counts reached 5% of the annual total pollen count, both in the SILAM model and in the observations. Timing the exact start of birch flowering is difficult; therefore, the limit of 5% was considered representative of flowering starting time or the early stage of flowering and of sufficient accuracy to be common for both pollen observations and model calculations. This method requires uninterrupted time series of pollen observations.

Model performance was studied in different areas of Europe, as defined in Figure 6.3. When all pollen stations that meet the quality criteria (Paper III) are taken into account, the SILAM model simulates birch flowering as beginning about 1 day–1 week too early, depending on the model settings. The smallest bias is achieved using the ECMWF model and LU-based temperature sum map (Figure 6.4a). Furthermore, the

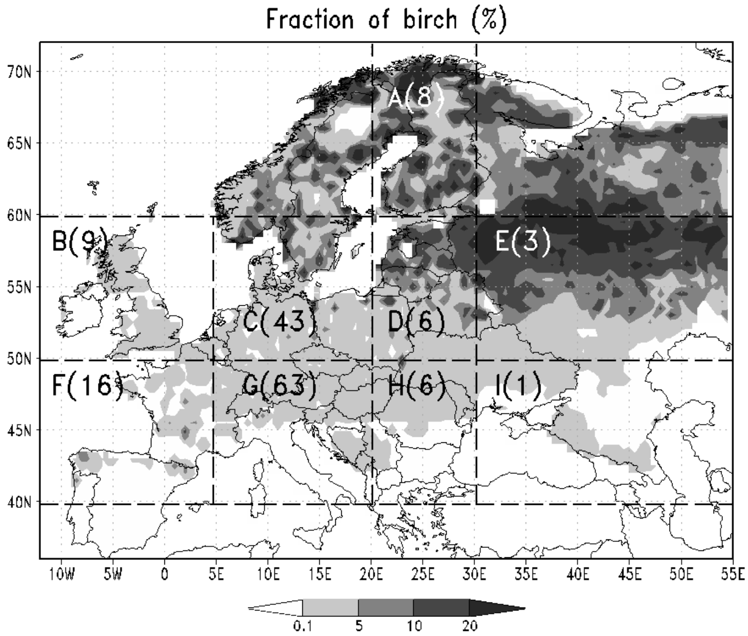
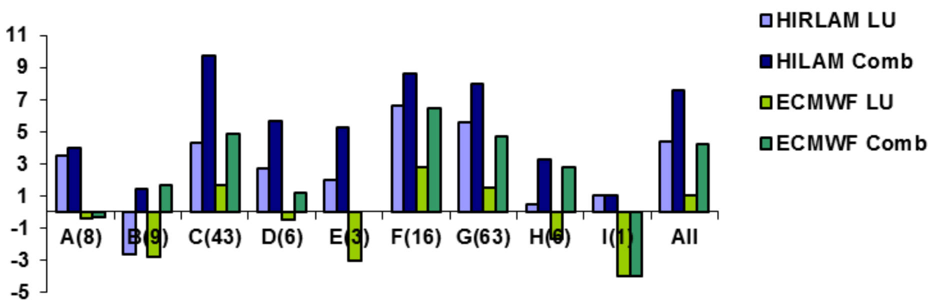
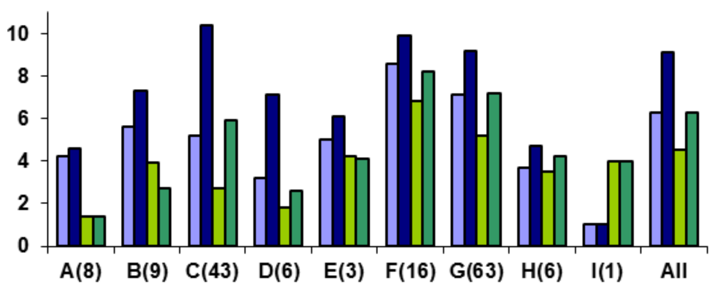


Figure 6.3 *The sub-regions considered for evaluating the SILAM model are delineated and labelled on top of the birch habitat map used in the 2006 SILAM pollen simulations. The numbers indicate the number of stations inside each area. (Paper III)*



a)



b)

Figure 6.4 *a) Bias (positive bias means flowering too early) and b) RMS error in days for the first flowering day predictions. The letters refer to the areas shown in Figure 6.3, together with the number of stations inside each area. LU denotes the leaf unfold–based temperature sum map, while Comb denotes the temperature sum map that combines pollen data with leaf unfolding.*

RMS error is also the smallest when using these settings (Figure 6.4b). On the other hand, the HIRLAM model and the combination temperature sum map produced the largest bias and RMS error. The reason for this is that HIRLAM is virtually always warmer than ECMWF, and low temperature sums obtained from pollen observations lead the model birch trees to bloom too early.
When the start of flowering is studied in smaller areas, the best predictions are provided for Finland and the Baltic countries (Areas A and D in Figure 6.3), which are the areas where birches are the most abundant, the climate is quite continental, and phenological observations are sufficient. The predictions are the least successful in Spain and France (Area F in Figure 6.3), where birch is not the major tree species. This area is also partly mountainous and near the Atlantic Ocean. This distribution of the skill of the forecast is also partly due to the fact that the critical temperature has been tuned to Northern European conditions.

Sakalli and Simpson (2012) also analysed the LU-based temperature sums presented in this study (Paper II) using the Pan-European Phenological Database (PEP) (PAN, 2011). Their goal was to retrieve the start of the growing season for a chemical transport model. According to their results, the correlation coefficient r^2 was 0.88, and the mean absolute error (MAE) was about 9 days. The LU-based temperature sums tends to predict leaf unfolding too early in early flowering areas and too late in areas of late flowering. However, this trend is not visible in our pollen observation–based analysis (Figure 6.4a).

Predicting the end of flowering is more difficult for the SILAM model. In this case, the end of flowering is estimated using pollen observations, with 95% of the total annual pollen count representing the end of the flowering. As a rule, the model birches pollinate for too long. At best, the bias in the Baltic countries is about ± 0.5 days, but in the worst case, around the Alps, the model birches produce pollen more than a week after the birches in the wild have already stopped pollination.

Contrarily to the start of flowering, HIRLAM and the combination map seem to be the best in this case. However, this is slightly a misleading result, since when analysing the whole flowering period, pollination stretches for about 10 days too long using the HIRLAM–combination pair, whereas the ECMWF–LU pair produces pollination for only about 6 days too long.

Prediction of pollen concentrations

Pollen release in the SILAM model is based on the so-called "open pocket" principle: pollen is released from catkins as long as it is left as presented in Eq. 5.6. The total amount of pollen developed in catkins, N_{total}, is a very uncertain parameter. Some regional studies show the possibility of predicting this parameter based on meteorological data and pollen production from the previous year (Rasmussen 2002; Ranta and Satri 2007; Ranta et al. 2008, 2011); however, in the model simulations for 2006, the amount of pollen was assumed to be constant almost everywhere in Europe, so that, in addition to weather conditions, only a fraction of the birch had scaled pollen release rates. In the northernmost part of Europe (latitude > 65°), where climate limits pollen production, N_{total} was set smaller; thus, the pollen release rate was smaller than the fraction of birch would suggest.

Since the parameter N_{total} is very uncertain, both observed and predicted total amount of pollen were scaled to correspond to each other throughout Europe on May 31. SILAM predicted pollen amounts that were multiplied by a factor, which varied from between 2.3 and 3, depending on the model configuration.

After scaling, the SILAM pollen model predicted the pollen concentration classes well. The number of low concentration cases (1–10 grains/m³) is slightly underestimated, and the numbers of moderate (10–100 grains/m³) and high concentrations (100–1000 grains/m³) were slightly overestimated (Figure 6.5).

Yet, this does not tell us how useful the SILAM pollen forecasts are. A variety of categorical verification quantities can be calculated if the observations and the model predictions are divided into two groups: less and more than 50 grains/m³.

Figure 6.6 shows some verification scores. The accuracy of the model is, at best, about 80%, regardless of the model setup, while the False Alarm Ratio (FAR) is less than 40%. The Hit Rate (HR), which indicates how well observed the moderate or high pollen concentrations are predicted, is about 70%, and the corresponding Probability of False Detection (F) is around 16%. Although ECMWF seems to have smaller FAR values, Hanssen and Kuiper's Skill Score (KSS = HR - F) yields the best results by using the HIRLAM–LU settings (54.9%) and the lowest using ECMWF–LU settings (48.5%).

The differences between the different model setups are limited. Generally, the ECMWF model has a slightly lower bias and RMS error than HIRLAM. When categorical verification quantities are analysed, the distinction is not unambiguous. Only the LU-based temperature sum map seems more predictive than the combination map.

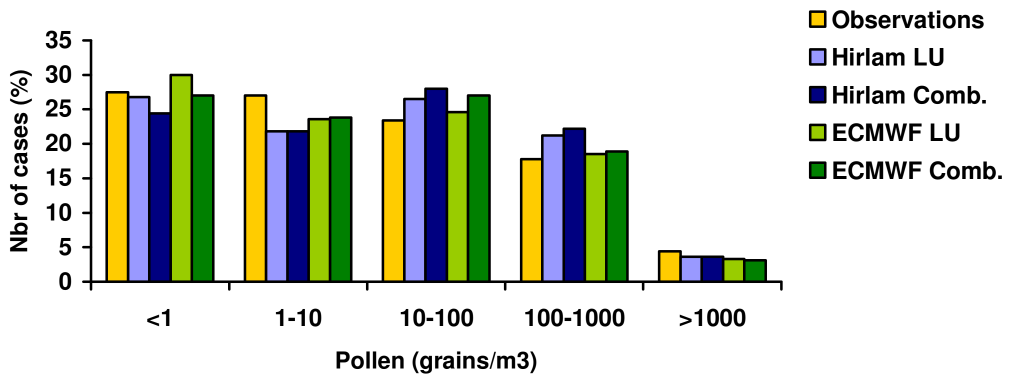


Figure 6.5 *Number of cases (%) when observed and predicted pollen counts are zero (< 1 grain/m³), low (1–10 grains/m³), moderate (10–100 grains/m³), abundant (100–1000 grains/m³), or very high (> 1000 grains/m³) (Paper III)*

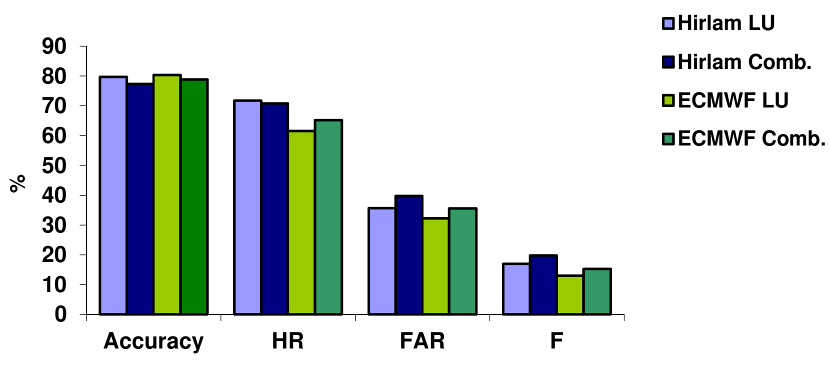


Figure 6.6 *Statistical scores of the performance of several SILAM setups for spring of 2006 (revised from Paper III)*

The ECMWF–LU setup was selected for closer examination. In situations where SILAM does not predict any pollen, or only small amounts (less than 10 grains/m³), 2/3 of the predictions proved to be true. In addition, about 20% of these cases are those in which the observations are not available, and thus, a correct classification is unclear. Therefore, we can approximate that 70–80 % of low-level cases were predicted correctly. Only in 4% of the cases did SILAM predict only minor concentrations, although observed pollen concentrations were abundant (more than 100 grains/m³); thus, SILAM does not tend to miss abundant pollen cases, which is important from a practical point of view. When SILAM predicts high concentrations, about 60% of these cases are correct, but about 10% of these predictions are clearly erroneous. Predicting moderate concentrations is challenging for SILAM. Only 35–40% of the cases belong to the correct category. Concentrations are under-predicted in another third of the cases, and in about a fourth of the cases, they are over-predicted.

Overall assessment

The SILAM pollen modelling system can help to create better and more accurate pollen predictions, but it is still too inaccurate for unedited automatic production and distribution to the public. The user of the model should have a good understanding of its limitations and weaknesses.

Our analysis for 2006, together with practical experience gathered over several years of using the system, show that the accuracy of the pollen concentration forecasts tends to be the best for the LRT episodes, which are usually caused by the pollination of large, albeit remote, birch forests. This is because the small-scale irregularities of the plume are smoothed out during transport, thus leading to good overall agreement with the observations. Near the source, even limited inaccuracies in the temperature sum prediction, birch distribution, or threshold values can immediately affect the agreement with observations at nearby stations. Furthermore, the relatively coarse spatial resolution of the model is also better adapted to simulating large, smoothed plumes.

A significant difference from traditional air quality predictions arises when the accuracy of specific concentration ranges is analysed. Usually, air quality models predict moderate concentrations well, but experience difficulties with low and high levels. The pollen model behaviour appeared to be quite the opposite: peaks and lows were better predicted than the moderate values! Several factors contribute to this peculiarity of pollen forecasting. One of the explanations comes from the specifics of the birch distribution in Europe. In Northern Europe, vast forested areas with a substantial fraction of birch constitute a very strong and wide area/source of pollen. In Central Europe, birch trees are still rather common but rarely form forests; rather, they are spread over small pieces of wild land and urbanised areas. In Southern Europe, birch is merely an exotic tree. Over areas characterised by a high fraction of birch forests, airborne pollen concentrations rapidly increase from low to high when pollination starts and quickly fade out when the flowering season is over. These areas are quite well-known. For such areas, dilution over the model grid cell is not a problem, since the source of pollen also covers a wide area. This explains why the high concentrations are well- reproduced. On the other hand, high forecasting scores for low concentrations simply mean that the flowering season is well-captured by the emission module, so that the low- or no-emission regions and time periods are correct.

On the contrary, moderate concentrations are more typical for areas where birch is not a dominant tree species, but rather, is spread around and mixed with other species, or sporadically planted as an ornamental tree. The quality of the birch map in such regions is expected to be lower, which affects the forecasted concentration scores.

Pollen has another strong difference from chemical and most other aerosol pollutants: it deposits quickly, yet even if low concentrations and small fractions of the overall emissions reach remote places, it can still have a strong impact there. Pollen counts can exceed tens of thousands of pollen grains/m^3 in the source regions, but the most sensitive people can experience allergic symptoms if concentrations are as low as 10 pollen grains/m^3. 100 pollen grains/m^3 is generally already considered to be abundant (Viander and Koivikko, 1978). The practical importance of low pollen concentrations is a challenge for the model, which should catch tails of several days–long episodes and also reproduce the start and end of local flowering when only a fraction of the trees are pollinating.

7 CONCLUSIONS

The main target of this study was to develop a bio-physical atmospheric dispersion modelling system that is able to predict birch pollen emissions and concentrations in Europe. The numerical forecasting of pollen concentrations is quite a new field. Most of the modelling attempts on regional or continental scales were performed after 2000 and are not numerous. The parameterisations, methods, and techniques are not as far advanced as, e.g., numerical weather forecasting or even traditional air quality modelling.

Numerical pollen dispersion models do not usually try to perform broad simulations; rather, they only focus on a small area or leave the flowering season aside completely and thus focus on just a few days during the flowering season. In this work, however, we have tried to simulate the entire chain of events from early spring, when birches start to prepare for the bud break; further, with the pollination phase; and finally, until the last northern pollen grains might be transported to the south. Furthermore, this comprehensive consideration covers the whole Europe.

Due to the broadness of the application area, both geographically and temporally, the model should be kept as optimally simple as possible. It is important to try to find the most relevant factors and add complexity only when the real needs and targets of development are identified. In addition, the model must be simple enough so that it can be easily run operationally.

The SILAM birch pollen forecasting system is a combination of many sub-models, which all have their strong and weak points. The system takes the meteorological fields from an external NWP model and strongly depends on its skill. However, the sensitivity of the SILAM pollen model to different NWP models proved to be quite small.

Uncertainties in the SILAM pollen modelling system

Since this work is the first version of a numerical birch pollen concentration and emission modelling system, many details could be further refined. Some statistical input data, such as the birch habitat map and the total amount of pollen released over the entire spring, directly affect model accuracy by transferring their own uncertainties. There is still a lack of knowledge on the distribution of birch trees in Europe, although some interesting new studies are fortunately emerging in this area (e.g., Skjøth et al. 2008b, Brus et al. 2011).

An even more uncertain parameter is the total amount of pollen grains that will be released from a unit area of birch forest during a specific flowering season. This amount is deduced from the number of catkins developed during the previous year. Its annual variability is wide (Koenig and Knops 2000; Stach et al., 2008), but the model does not take this into account. For example, several pollen monitoring sites observed a daily average of about 20–30 thousand birch pollen grains/m^3 in Finland during the spring of 2012, whereas in the next year, the local birch flowering peak values were less than 1% of this high value. The inter-annual variation of flowering intensity can, to some extent, be predicted from the previous year's information (Ranta et al., 2008, 2011). However, the method only explains a fraction of the variability and seems to be highly data-sensitive.

Uncertainties in constant parameters linearly propagate into concentration errors. In our study, the annual pollen count was normalized to the mean observed values over

Europe in 2006, thus correcting the bulk impact of these factors. However, regional inhomogeneities were not corrected.

The SILAM pollen modelling system has been evaluated in depth only for a single year. This is not enough to provide a proper understanding of the model behaviour, especially having in mind the strong inter-annual variability of phenological events. Thus, more systematic evaluations are needed.

Phenology

Schaber (2002) noted that there is no plant phenological model that would be applicable at the same time for several species and for wide geographical areas. He hypothesises that the reason for such a situation is the lack of both comprehensive phenological and weather observation data. Thus, model parameters are usually tuned to be site-specific in phenological models.

In order to predict the start of flowering in the SILAM pollen model, the phenological data had to be collected country-by-country, as there was no sufficiently comprehensive phenological database for Europe. When the collected data were analysed, it was found that the representativeness of these phenological observations was low. However, this is probably not due to the poor quality of the data, but to the inherent nature of phenological observations in general.

Schaber (2002) showed that the approximate average standard deviation of the combination of observers (1.5 days) and genetic error (7.6 days) was 9.1 days in Germany, which is in line with the result shown in this study (variability between 7–16 days).

We selected a simple linear temperature sum model for the start of flowering. Other studies (e.g., Linkosalo et al., 2008) have shown that it is as good as more complex models under boreal and temperate climate conditions. As the pollen forecasting system itself includes many other uncertainties that are induced by the NWP and atmospheric dispersion models, simplifying the phenological model does not significantly increase uncertainty, or at least keeps it under sufficient margins. Chilling days could, however, be useful in southern Europe and in the UK, for instance.

In our study, the representativeness of the weather parameters for the phenological model is addressed by using analysed screen-level temperatures from the ERA-40 re-analysis data, instead of actual weather observations. Since the weather data have to be injected into a grid-based numerical atmospheric dispersion model, with the results being grid-cell averages, such re-analysed data from the NWP model represent the best knowledge of atmospheric conditions at a particular time and thus can be expected to provide decent temperature approximation at the phenological observation sites. As far as we know, there has not been any attempt to calculate the phenological model parameters using a NWP model values before.

The prediction of the flowering starting time in SILAM is based on the long-term temperature sum computation, which is sensitive to the temperature bias in the NWP-model. The accumulation period before reaching the temperature sum threshold can be as long as 2–3 months, and a temperature bias of even 0.5º C would lead to an error of 30–50 DD in the temperature sum. This level is comparable to the threshold itself (Figure 5.2) and evidently leads to a prediction error of a week or more in the flowering starting date.

In comparison with the pre-season, the estimation of the pollen release and dispersion during the main flowering period poses challenges that are more familiar to air quality modelling practices. Precipitation and humidity can delay or inhibit pollination, while wind and turbulence promote it. The transport patterns are affected by regional- and synoptic-scale weather, turbulence, clouds, and other parameters describing dispersion conditions within and above the atmospheric boundary layer. Also, specific weather processes may be simulated with different accuracy by different NWP systems.

Footprints of LRTed pollen

Backward trajectories are the most popular way to determine the source areas of LRTed pollen. However, atmospheric dispersion models are more reliable and effective tools for the assessment of pollen source areas (Veriankaitė et al. 2010). Although trajectory models are simple to use, interpreting the results requires experience and understanding of atmospheric behaviour.

In our work, pollen source areas were tracked back by computing footprints using the SILAM dispersion model. Typical LRTed pollen, both in Finland and Moscow, originates from the southern sector. Observed pollen LRT occurring just before the start of flowering can also be transported from the west, or even from the northwest, from the Moscow area.

Surprisingly, Sweden rarely acts as a source area for LRTed birch pollen in Finland, although birch is a common tree species in Sweden, its flowering starts earlier, and westerly winds are dominant in Finland. The cold Baltic Sea may possibly suppress upward air motions and prevent the dispersion of large amounts of pollen. Instead, abundant pollen counts are observed when pollen LRT comes to Finland from Russia, where vast birch forests grow and with no major cold sea areas along the way.

Applications and future work

The main objective of this work was to produce a numerical forecasting system for allergenic pollen. Birch is presented in this study; however, forecasts are also necessary for other allergenic plants. In addition to birch, numerical predictions have also been performed at FMI for grass, olive, and ragweed. Also, alder pollen forecasts would be useful, since alder has a significant role in allergic symptoms for Europe.

Numerical weather prediction models deliver a large number of different automatic or semi-automatic weather products on the Internet, mobile electronics, and newspapers. Therefore, numerical pollen forecasts could also start using brand new ways to disseminate pollen predictions to the public. Analogously to numerical weather forecasts, for example, pollen forecasts for several locations, including the diurnal variation, could be possible.

Pollen concentrations can also be estimated under future climate conditions using a climate model as the source of weather information, instead of a NWP model. This is already done for ragweed pollen by using different climate change scenarios in Europe (Bullock et al. 2012).

Although pollen forecasts for the public are a direct, intuitive application, the model can be used for many other purposes. The next step after pollen forecasts is allergen predictions. Allergens cause allergic reactions. They are very small — with less than 1 μm particles — and are transported and removed from the atmosphere in different ways than heavy pollen grains. However, the release mechanisms of allergens from pollen grains is not yet well-known; thus, the allergen content in the atmosphere can be predicted using numerical pollen forecast models (Rantio-Lehtimäki 1994;

Buters et al. 2012). Studying allergens also implies addressing the complex interactions between air pollution, pollen, and allergens (Emberlin 1995; Buters et al. 2012).

Gene flows of plants with quick atmospheric pathways for the genetic material of remote populations can be important for the plants' adaptation to rapid climate change (e.g., Kremer et al. 2012; Paper V). Also, gene manipulation studies can determine the possibility of GMOs to escape into pristine nature (e.g., Kuparinen et al. 2007). Microscope analyses of pollen cannot separate local pollen from LRTed pollen grains, but the model can easily do so. Pollen dispersion simulations merely need to be run using a small source area around the observation site and compare fractions when the model source is enlarged. Also, paleopalynological studies could benefit from the model's ability to estimate dispersion distances, both in forward and footprint mode.

Birch bud bursts start the green wave observed by satellites (Karlsen et al. 2009). Since SILAM predicts the temperature sum for birch leaves unfolding all over Europe, NWP, climate, and air quality models could utilize it, which would enable taking into account the effect of the leaf area index (LAI) on boundary layer conditions, rather than only using climatology (Sakalli and Simpson 2012). With small modifications, the SILAM pollen model could also be used as part of the warning system for migrations of pest insects (Leskinen et al. 2011).

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